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53, Rustaveli Avenue, Batumi, 6010, Georgia

Tel: +995 032 2887337

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Quantitative Gaze Similarity Analysis for Operation-based Maritime Studies: A Conceptual Approach

Khairul Izzati bin Kamarumtham[1]*, and Koji Murai[2]

[1] Sugahara Kisen Co., Ltd., Japan

[2] Tokyo University of Marine Science and Technology, Japan

* Corresponding author: d232004@edu.kaiyodai.ac.jp;

Abstract. Video-based eye-tracking technology has demonstrated promising potential for quantitatively assessing the mental states of maritime professionals, particularly perceptual performance related to situational awareness—a critical competency for operators of both conventional and crewless ships. Quantitative evaluation of perception can support the enhancement of training curricula for conventional operators and accelerate the development of effective training frameworks for remote operations of unmanned ships. One approach to evaluating perceptual performance is gaze similarity analysis; however, existing quantitative methods for operation-based experimental settings incorporate subjective elements, which may limit analytical accuracy and reproducibility. To address this limitation, this study proposes a conceptual, quantitative gaze similarity analysis method that does not rely on subjective judgment. The method is demonstrated through an experiment involving simulated remote ship operations. In the experiment, a participant wearing a mobile eye-tracker monitored two navigational scenarios: southbound and northbound passages through the Uraga Channel traffic route. Fixation data obtained from both scenarios were analyzed using the proposed method. The results indicate that gaze similarity can be quantitatively assessed in operation-based experimental settings using data derived directly from operational tasks, thereby providing an alternative framework that complements existing approaches for evaluating perceptual performance among maritime professionals.

Keywords: eye movement, gaze movement, image processing, seafarer, shore-based operator

1. Introduction

Situational awareness (SA) has been widely recognized as a critical non-technical skill for maritime professionals. Numerous studies investigating the competencies required of future seafarers — whether operating onboard conventional vessels or from shore-based remote control stations — consistently identify the ability to maintain adequate situational awareness as essential for safe and effective operations (Bogusławski et al., 2022; Chan, Norman, et al., 2022; Chan et al., 2025; Chan, Pazouki, & Norman, 2022; Kim & Mallam, 2020; Yoshida et al., 2020). As maritime operations become increasingly complex, particularly with the emergence of unmanned and remotely operated vessels, the importance of understanding and assessing situational awareness continues to grow.

Reflecting this importance, a growing body of literature has examined situational awareness among maritime professionals (Chan, Norman, et al., 2022; Chan, Pazouki, & Norman, 2022; Palbar Misas et al., 2024; Veitch et al., 2024). In parallel with these efforts, eye-tracking technology has been increasingly adopted as a means of investigating the cognitive states of maritime professionals (Kamarumtham et al., 2026; Martinez-Marquez et al., 2021). By capturing gaze behavior, eye-tracking provides quantitative insight into perceptual processes, which constitute one of the fundamental building blocks of situational awareness during navigation and operation tasks.

Building on the use of eye-tracking to investigate perceptual processes, several studies in the maritime domain have explored quantitative methods for analyzing gaze behavior. These studies generally assess novice operators' performance by comparing their gaze patterns with those of experts (Atik, 2020; Atik & Arslan, 2019; Godwin et al., 2013; Kamarumtham & Murai, 2025; Li et al., 2020; Mao et al., 2019; Muczynski et al., 2013). Nonetheless, to date, only a limited number of studies have specifically addressed the development of gaze similarity analysis methods in the maritime context, including two focused on operation-based experimental settings (Li et al., 2020; Mao et al., 2019) and one focused on screen-based experimental settings (Kamarumtham & Murai, 2025). Although participant numbers in these studies remain limited, their findings indicate promising potential for enhancing training curricula for maritime operators working on both conventional and unmanned vessels.

Despite this progress, methodological limitations remain. In particular, the gaze similarity analysis methods developed for operation-based experimental settings incorporate subjective elements in their analytical procedures (Li et al., 2020; Mao et al., 2019). While these approaches represent an important step forward in the quantitative assessment of perceptual performance, the inclusion of subjective components may limit analytical accuracy, reproducibility, and broader applicability across different operational contexts. Moreover, another existing gaze similarity analysis was specifically designed for screen-based experimental settings; thus, it is unsuitable for operation-based experimental settings (Kamarumtham & Murai, 2025). Additionally, Martinez-Marquez et al. (2021) reported that although eye tracking has been widely applied in aviation and construction research, no gaze similarity analysis methods had been introduced in either field.

In response to this limitation, the objective of the present study is to introduce and demonstrate a conceptual gaze similarity analysis method for operation-based experimental settings that does not rely on subjective elements. By adopting a fully quantitative approach grounded in operational data, this study aims to provide an alternative methodological framework for assessing gaze similarity and perceptual performance among maritime professionals.

2. Methodology

2.1 Operation-based & Screen-based Experimental Settings

Eye-tracking studies in the maritime field can be broadly grouped into two categories based on the experimental setups: (1) operation-based and (2) screen-based. Operation-based setup refers to experimental settings where participants perform tasks in full-mission simulators, actual ships, or environments that closely resemble real-world operational settings. This setup commonly uses mobile eye trackers, eye-tracking devices that are worn by users, allowing the users to move freely within the experimental settings. Alternatively, screen-based setup refers to experimental settings where participants perform tasks presented via a single-screen interface, commonly in controlled laboratory settings. This setup commonly uses remote eye trackers, which do not require physical attachment to users and allow them to interact with digital interfaces more naturally. Table 1 summarizes the advantages and limitations of each setting. As mentioned in the previous chapter, this study will introduce a gaze similarity analysis method designed for operation-based experimental settings.

Table 1. Advantages and Limitations of Operation-based and Screen-based Experimental Settings.

Operation-based Experimental Settings	Screen-based Experimental Settings
Advantages	**Advantages**
- Higher ecological validity and more realistic operator behavior representation. - Better reflection of workload and situational awareness in real operations.	- Simpler and more controllable experimental setup. - Easier and less time-consuming data collection and analysis. - Higher experimental reproducibility.
Limitations	**Limitations**
- More complex and resource-intensive experimental setup. - More complicated and time-consuming data collection and analysis.	- Lower ecological validity. - Limited representation of real operational behavior and decision-making.

2.2 Eye-tracking Technology

In this study, a mobile eye tracker, EMR-9, was used (see Figure 1). The eye tracker was selected because it supports gaze recording in dynamic operational environments, which is a fundamental requirement for operation-based eye-tracking studies. As the primary objective of this study is to introduce and demonstrate a conceptual framework for gaze similarity analysis, priority was given to obtaining sufficient gaze data while maintaining a manageable data analysis process when configuring the system settings for the eye tracker. Table 2 summarizes the settings used in this study. To analyse

Figure 1. EMR-9
(Left: Cap-type, Middle: Glasses-type, Right:

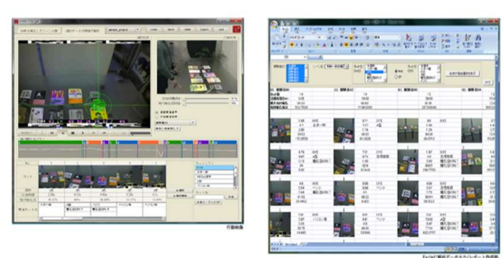


Figure 2. EMR-dTarget
(Left: Eye Mark Recording, Right: Excel Ouput)

the participant's fixation behavior, the accompanying analysis software, EMR-dTarget, was used (see Figure 2).

Table 2. EMR-9 eye-tracking system settings

System Type	☐ Cap	☑ Glasses		
Sampling	☑ 60 Hz	☐ 120 Hz	☐ 240 Hz	
Lens	☑ 44°	☐ 62°	☐ 92°	☐ 121°
Algorithm (Eye Mark Detection Method)	☑ Standard	☐ Pupil	☐ Purkinje	

Detailed explanations of these and other parameters can be found in the eye tracker's manuals (nac Image Technology, 2009, 2011)

2.3 Experimental Settings

To demonstrate the feasibility of the proposed conceptual method, at least two sets of fixation data are required for comparison. Accordingly, this study conducted a small-scale illustrative experiment involving a single participant performing two simulated remote ship operations. The participant was a final-year undergraduate student at the Tokyo University of Marine Science and Technology, majoring in Maritime Systems Engineering, and had completed two months of onboard training as a deck cadet.

The simulated remote ship operations comprised two navigational scenarios—southbound and northbound transits—along the Uraga Channel traffic route. In the southbound scenario, the ship transited the traffic route from point A to point B, whereas in the northbound scenario, the ship transited from point C to point D (see Figure 3), and both operations lasted 29 minutes.

The participant was provided with three monitors displaying ECDIS, bridge view, and RADAR information (see Figure 4). The instruction given to the participant was as follows: "Please imagine yourself as the officer in charge, performing monitoring duties in a remote ship operation".

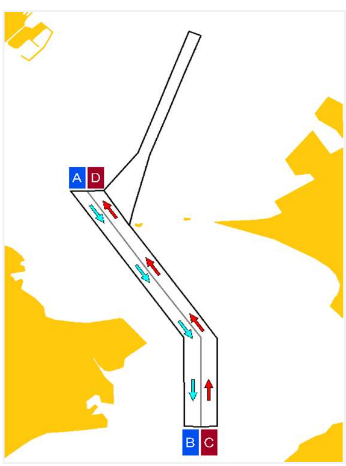


Figure 3. Southbound and Northbound Transits along the Uraga Channel Traffic Route

Figure 4. Experimental Setup of the Simulated Remote Ship Operations

2.4 Gaze Similarity Analysis

To measure the similarity between the two sets of fixation data obtained from the southbound and northbound operations, the monitors showing the ECDIS, bridge view, and RADAR were assigned as areas of interest (AOIs). Each AOI was subdivided into a grid of cells (see Figure 5), with each cell measuring 120 × 120 pixels. Given that the resolution of each AOI was 1920 × 1080 pixels, each AOI comprised 144 cells.

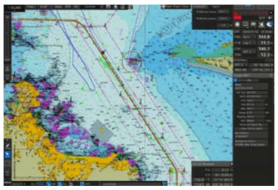
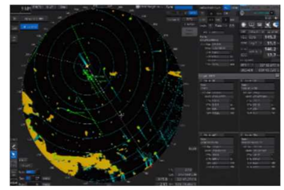
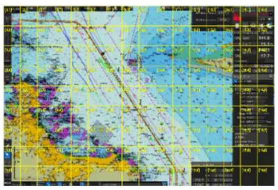
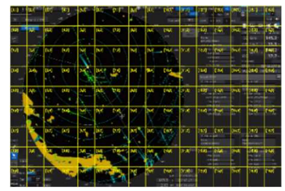
ECDIS	Bridge View	RADAR
		
		

Figure 1. AOIs (Upper) and Gridded AOIs (Lower)

While Holmqvist and Andersson (2011) have defined fixations using thresholds ranging from 0.2 to 0.4 s and above, a threshold of 0.4 s was adopted for two reasons: (1) the data analysis process was time-consuming, and (2) the primary objective of this study was to demonstrate the feasibility of the proposed conceptual method rather than to determine optimal parameter settings.

Next, the total fixation duration within each cell was calculated. This process resulted in two sets of three two-dimensional arrays, each representing the spatial distribution of fixation durations across the AOIs. Subsequently, each two-dimensional array was converted into a one-dimensional array, and the resulting arrays were concatenated to form a single one-dimensional array for each operation. Consequently, two one-dimensional arrays were obtained, representing the fixation data from the southbound and northbound operations. The similarity between these two fixation datasets was then quantified using three gaze similarity indices: (1) Spatial Similarity Index (SSI), (2) Spatial–Temporal Similarity Index (STSI), and (3) High-Salience Similarity Index (HSSI).

2.5 Gaze Similarity Indices

a. Spatial Similarity Index (SSI)

SSI quantifies similarity between two fixation datasets based solely on the spatial distribution of fixations, independent of fixation duration. This is achieved by converting all cells with nonzero values to 1 and assigning 0 otherwise, thereby retaining only spatial fixation information. The SSI between the resulting binary datasets is computed using the Dice coefficient (1), yielding similarity values ranging from 0 (no overlap) to 1 (perfect overlap).

b. Spatial-Temporal Similarity Index (STSI)

STSI quantifies similarity between two fixation datasets by considering both fixation areas and their associated durations. This is achieved by retaining the original cell values, which represent accumulated fixation duration. The STSI between the two datasets is computed using cosine similarity (2), producing values between 0 (no similarity) and 1 (perfect similarity).

c. High-Salience Similarity Index (HSSI)

HSSI quantifies similarity between two fixation datasets by focusing on fixation areas with the highest salience. Specifically, the original values of cells corresponding to the top 10% of fixation durations are retained, while all values in the lower 90% are set to zero. The HSSI of the resulting high-salience fixation datasets is computed using cosine similarity (2). As with STSI, HSSI values range from 0 (no match) to 1 (perfect match).

$$Dice\ Coefficient = \frac{2\sum_{i=1}^{n} X_i Y_i}{\sum_{i=1}^{n} X_i + \sum_{i=1}^{n} Y_i} \tag{1}$$

$$Cosine\ Similarity = \frac{\sum_{i=1}^{n} X_i Y_i}{\sqrt{\sum_{i=1}^{n} X_i^2} \cdot \sqrt{\sum_{i=1}^{n} Y_i^2}} \tag{2}$$

Where:

$$X_i = value\ of\ the\ i-th\ cell\ in\ the\ gaze\ pattern\ for\ Southbound\ Operation$$

$$Y_i = value\ of\ the\ i-th\ cell\ in\ the\ gaze\ pattern\ for\ Northbound\ Operation.$$

3. Results

3.1 Fixation Areas and Durations

a. Southbound Operation

Figures 6, 7, and 8 show the participants' fixation areas and durations (in seconds) during the southbound operation.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1															0.74		1
2						0.45		1.37	3.09	0.82					0.66	3.97	2
3						4.6	28.5	30.11	21.09							4.24	3
4					3.02	4.85	21.34	7.98	16.89			0.89					4
5						2.25	9.97	19.99	57.83	8.6							5
6							0.98	13.21	23.61	5.54	1.19					0.64	6
7							0.52	2.17	5.61		1.58	8.03		0.8			7
8									3.6	3.65	3.5						8
9																	9
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	

Figure 2. Participant's Fixation Data for ECDIS during Southbound Operation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1		0.43					2.07	1.89	5.02	6.66	1.98	2.01	4.51	2.42	0.73	0.49	1
2			1.19	3.59	0.86	3.17	5.16	13.78	13.18	11.25	4.46	3.46	4.47	1.09	3.18		2
3				4.98	5.11	5.5	16.18	12.95	25.29	18.04	17.65	6.71	3.56	4.55		1.05	3
4	1.72	1.92	2.95	5.26	11.01	13.45	28.39	30.76	23.1	16.31	14.78	14.82	3.13	4.52	2.39		4
5	1.44	1.61	1.95	4.72	10.31	8.44	29.79	31.65	34.66	22.87	11.53	5.39	3.82	1.91	1.91		5
6	0.9	1.75	2.28	1.8	1.78	10.15	20.68	10.86	15.09	7.17		4.52	4.52	2.08			6
7			2.03	2.36	0.88	1.08	7.86	4.62	8.09	6.81	6.32	1.88	1.95	0.57	0.52		7
8					0.55		0.55		1.9	7.32				1.53			8
9								0.66	2.29								9
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	

Figure 3. Participant's Fixation Data for Bridge View during Southbound Operation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1	0.48				0.64												1
2												1.33	1.86				2
3				1.99	6.38	5.61	0.62	0.4									3
4	1.16	0.84		1.19	51.37	17.07	1.33						2.77				4
5					1.79	29.52	19.46	9.25					1.25	1.01			5
6	0.73		16.78			17.25	34.82	2.82				6.26	3.22				6
7					10.8	10.11		3.96					0.91			1.87	7
8				1.25					3.08			1.33			5.54	1.33	8
9									1.42	2.92							9
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	

Figure 4. Participant's Fixation Data for RADAR during Southbound Operation

b. Northbound Operation

Figures 9, 10, and 11 show the participants' fixation areas and durations (in seconds) during the southbound operation.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1						1.72									0.9	2.24	1
2					3.85		13.3	1.61				0.76		0.48	1.14	1.19	2
3							2.53	17.19	25.08			0.7	3.27	3.47	1.19	1.04	3
4					2.32	11.04	5.58	22.1	2.08	3.87		1.59		1.63	2.91		4
5				0.85		7.9	22.41	15.24	16.46	0.92		0.51	0.57	0.76	1.59	1.27	5
6				0.52		1.63	7	10.87	8.8	30.33		4.19		7.31	0.54	0.61	6
7							4.73	3.46	0.97	1.1		1.03	2.31		2.9		7
8								2.12						2.3	1.48	8.83	8
9										1					1.34		9
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	

Figure 5. Participant's Fixation Data for ECDIS during Northbound Operation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1			0.62		0.44	0.44	4.59	0.58	2.25	4.63	8.86	1.79	2.69				1
2		3.52	2.83	2.38	4.95	1.1	1.46	2.92	9.73	3.98	1.11	1.99	1.42	1.7			2
3	1.08	6.63	2.77	9.66	5.98	11.66	9.96	12.15	9.08	14.1	5.06	2.77	3.23		1.77	0.97	3
4		0.99	10.06	14.77	6.23	5.74	15.4	14.86	11.04	14.47	10.47	8.49	1.38	3.79	1.09	1.71	4
5	0.64		6.12	3.76	5.01	8.93	8.79	12.82	12.71	23.32	12	5.03	6.38	0.53	0.92	0.42	5
6	5.54	1.69	3.89	6.6	22.22	2.43	4.8	11.81	13.94	10.57	7.67	5.96	3.89		1.45	0.43	6
7	0.66	2.88		6.42	6.63	4.72	5.71	5.81	11.78	2.22	2.34	1.28	1.66	1.06		1.48	7
8		0.63		2.03	1.88	0.8	8.76		1.87	1.73	0.88		0.8		0.4		8
9		1.07						0.58	1.05		1.12						9
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	

Figure 6. Participant's Fixation Data for Bridge View during Northbound Operation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1	1.25	0.54															1
2		0.57		0.48													2
3				4.23	2.3	7.04	0.42	0.8									3
4	3.5		0.91		5.23	4.16	3.16										4
5				2.3		4.22	3.16						0.75				5
6	1.96		0.75		2.6												6
7																	7
8		1.29					0.6						0.63				8
9																	9
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	

Figure 7. Participant's Fixation Data for RADAR during Northbound Operation

3.2 SSI, STSI, and HSSI

Table 3 presents the percentages of SSI, STSI, and HSSI for the two fixation datasets.

Table 3. Similarities between participant's fixation data during southbound and northbound operations

Gaze Similarity Indices	**Similarity Percentages**
Spatial Similarity Index (SSI)	66.3
Spatial-Temporal Similarity Index (STSI)	61.0
High-Salience Similarity Index (HSSI)	62.3

4. Discussion

The SSI, STSI, and HSSI values obtained for the two gaze datasets were 66.3%, 61.0%, and 62.3%, respectively. Given that both datasets were generated by the same participant performing similar monitoring tasks, higher similarity scores might initially be expected. However, several operational and human-related factors may explain the observed differences in gaze behavior between the two operations.

First, although both operations were conducted in the same geographical area, the surrounding traffic conditions differed in terms of traffic density and vessel approach direction. Variations in traffic situations are likely to influence visual attention allocation, particularly toward information-intensive displays such as the ECDIS and RADAR. Consequently, differences in traffic scenarios may have resulted in shifts in fixation distribution across these interfaces. Second, the nature of the monitoring task itself may have influenced gaze behavior. Monitoring tasks are relatively passive and may induce reduced vigilance over time. As the experiment involved consecutive operations, the participant may have experienced a decline in attention or focus during the second operation, leading to variations in fixation patterns. Finally, a learning or adaptation effect may also account for the observed discrepancy in gaze similarity. The participant may have required an initial period to become familiar with the simulated operational environment and display layout, resulting in differences in visual scanning strategies between the first and second operations.

Importantly, the purpose of this study is not primarily to establish empirical findings regarding operator performance or human behavior under specific maritime conditions. Rather, the main contribution of this study is methodological: to demonstrate that the proposed conceptual framework can quantitatively evaluate gaze similarity in operation-based experimental settings and produce interpretable outputs linked to operational behavior. In other words, the obtained similarity values should not be interpreted merely as numerical indicators, but as quantitative representations of underlying differences in visual attention allocation and scanning strategies.

From this perspective, the moderate similarity scores observed in this study are meaningful because the proposed framework generated quantitative outputs that correspond plausibly with identifiable operational and cognitive factors, such as traffic conditions, vigilance changes, and adaptation effects. The ability to relate the resulting similarity indices to interpretable behavioral and contextual differences suggests that the framework can support not only quantitative comparison of gaze data, but also analytical interpretation of why particular similarity values emerge.

Taken together, these findings support the feasibility of the proposed framework as an alternative quantitative approach for gaze similarity analysis in operation-based experimental settings. The study therefore serves primarily as a proof-of-concept demonstration of the framework's applicability and interpretability, rather than as a definitive empirical investigation of maritime operator behavior.

5. Conclusion

This study introduced and demonstrated a conceptual, quantitative gaze similarity analysis method for operation-based experimental settings. The results indicate that the proposed method has potential as an effective alternative framework for quantitatively assessing gaze similarity without reliance on subjective elements. By deriving similarity measures directly from operational data, the method offers a structured approach to evaluating perceptual performance in maritime contexts. Nevertheless, one notable limitation of the proposed method is that the data analysis process is time-consuming, which may restrict its applicability in large-scale studies. The integration of deep learning–based techniques presents a promising direction for overcoming this limitation by automating and accelerating key stages of the analysis pipeline.

Future work may focus on incorporating deep learning approaches to reduce analysis time and improve scalability. Additional efforts should also consider systematic adjustments of experimental parameters, including eye-tracker settings, fixation duration thresholds, and the number and size of spatial cells, to examine their influence on gaze similarity outcomes. Validation of the proposed similarity indices against operator performance, situational awareness, and expert gaze behaviour should also be investigated to further evaluate the analytical effectiveness and practical relevance of the framework. In addition, future studies should aim to establish clearer interpretative benchmarks for similarity values by comparing results across different operational conditions and participant groups. Furthermore, expanding the sample size, diversifying participant backgrounds, and including a wider range of operational scenarios will be essential for evaluating the generalizability and practical applicability of the proposed method in maritime training and operational environments.

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Increasing the Reliability of Ship Refrigeration Units Through Permanent Control of Refrigerant Leakage

Maia Tugushi*[1], Vazha Sikharulidze[1], Mikheil Lejava[1], Zaza Shubladze[1], Gocha Gogitidze[1], Firuza Varshanidze[1]

[1]Batumi State Maritime Academy, Georgia

*Corresponding author: m.tugushi@bsma.edu.ge

Abstract: Refrigerating plants on board are used in refrigerating holds, gas carriers, and refrigerating chambers for receiving and maintaining low temperature, for conditioning air at all seasons, and other purposes. Separate elements of the refrigerating machines are cooled by fresh or seawater. That's why the metal should be corrosion-proof. The installation should be lightweight, stand out with simple maintenance, be cheap, and economical.

It is necessary to keep not only the main operating parameters, but also to control the operation of its separate elements. It is important that the refrigerant does not have leakage of freon, which will cause the poisoning of the service personnel and ecological damage. Various kinds of sensors are used, which react to the leakage of freon. Practically, their acting is expressed by activating of alarm.

The purpose of this article is not only the discussion of activation of the signaling system of the refrigerating installation, but depending on the situation freon supply valve shut-off system and after a certain delay (if there was a delay in involving the personnel to eliminate the faculties), to discuss the action of shut off system of installation.

Keywords: refrigerating plant, freon, signaling system.

1. Introduction

For improving the reliability of the operation of the refrigerating machines, it is provided the duplicating of the machinery is provided without shutting off the operation for carrying out the repair work. The ship's refrigeration equipment may include one or more/duplicated refrigerating machines, installations for various duties and systems, devices for controlling, protecting, signaling, automated controlling systems, and adjusting devices, which provide the normal operation of the refrigerating machines (Hafner Ing. A., Gabrielii C.N. & Widell K, 2019).

According to the temperature mode, refrigerating ships are divided into low temperature, which are designed for frozen products, universal, any kind of cargo, and fruit carriers, with induced ventilated compartments.

It's important not to allow a leakage in the refrigerating plant – leakage of freon (British Refrigeration Association Action Group, 2018). The leakage of freon has effects, such as reducing cold productivity, which is followed by damage to perishable goods and cargo (Running parts will make an uncharacteristic sound; Oily stains and damages on refrigerator components; generation of harmful emissions that are harmful to the environment and human health).

To avoid these problems, it's necessary to check regularly all refrigerating plants for detecting mechanical damage and corrosion spots. Also, regularly must be checked the freon pressure, according to the manufacturer's instructions must be carried out its filling and adding (European Commission, 2006 & European Commission, 2014).

To avoid the freon leakage signaling system must be used, which will fix the pressure drop in the refrigerating system (НПО «РУСХИМПРОМ»,2026).

Locating the leak and responding to it promptly remains a problem.

Prolonging the time of freon leakage may result in serious environmental damage and a reduction in the cooling capacity of the unit.

Under the influence of ultraviolet radiation, the chlorine atom begins to separate the freon molecules, remains in particles, and starts rusting.

It results in new radical chlorine particles being formed, which interact with the ozone layer in the air and enter a chemical reaction. This impact is a prerequisite for the depletion of the ozone layer in the atmosphere. If damage occurs frequently, it can cause ozone holes, global warming, and greenhouse gas emissions.

Based on the above, all measures aimed at reducing the leakage are essential.

2. Main part

The research discussed in the article aims to reduce losses caused by malfunctions during the operation of refrigeration equipment, developing an additional signaling system for reducing emissions. Based on the signal recorded during the usage of pressure relays, not only should the alarm system operate, but also the supply chain of freon should be affected by the lockdown. If the leakage from the damaged outlet continues, the control system must ensure that the unit is stopped.

To achieve the research goals, an alarm and refrigeration unit freon supply valve control system should be created.

The operation of the compressor is evaluated by controlling measuring instruments, by its physical condition, with the sound of working nodes, temperature of various parts, oil, refrigerant pressure, temperature, and level.

Operation of the piston compressor is accompanied by the rhythmical knock of suction and discharge valves. A malfunction of the suction and discharge valves is indicated by a rapid increase in pressure on the stopped compressor. Also, looseness of the suction and discharge valves indicates an increase in temperature of the compressor (when there is no cause). Running parts in operating machinery emit a characteristic sound that changes with the working conditions of the nodes.

With the change of pressure, meaning it’s possible to detect the freon leakage, and with the alarm signaling and control system, provide timely detection and stopping of the leakage.

For detecting the freon leakage, the transferring sensor FROI -24/220 (MRS Elektronik, 2026) is used. Its operating principle is based on a change in the electrical conductivity of a lead oxide semiconductor layer, as a result of the adsorption of a controlling gas on its surface.

The selective property of the sensor is ensured by the presence of regulating additives in the semi-permeable membrane. The micro heater is used to increase the speed of reaction. The gas sensor used in the transmitter provides high sensitivity to the concentration of freon in the air at the level of the tenth part of ppm level. The transmitter gives a sound or light signal. The research team suggests that the technical personnel’s response to the alarm delay adds to the engine of the freon propulsion system a blocking signal, which will activate after a short delay of time by disconnecting the switching off normally closed contact of the **KM** contractor.

FR01-24/220 sensors' correct operation during technical work is checked in three ways:

1. Using the ethanol steam
2. Using the freon leakage simulator
3. Using the complex of calibration based on R134A-air mixture freon (1000 ppm concentration).

Under the basis on the developed principal scheme (Fig. 1) is possible to provide correct operation of the sensor. Considering that the aim of the researchers is the improvement of the existing controlling system, which is connected with the total change of the system, it will be easy to implement in existing operating systems.

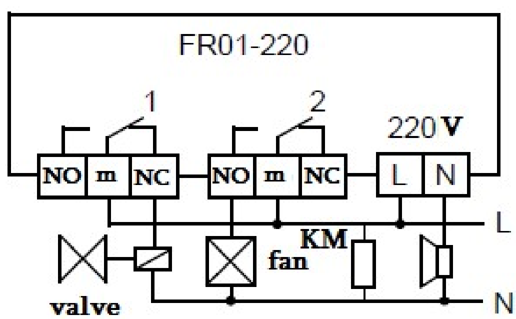

Fig 1. Freon propulsion system engine Blocking signal circuit diagram.

As we have already mentioned, the problem is urgent and concerns not only the ship’s refrigeration units, but also all refrigeration units on land. The number of the latter is very large, and the result obtained by controlling the leakage of freon in each of them, even if the volume is small for one device, will contribute to solving a very large ecological problem in total.

3. Conclusion

In addition to the alarm and control system, the corresponding relay-contactor in the drive control circuit for locking the coolant supply valve and shutting down the refrigeration unit will be activated to stop emissions on time.

The development appropriate alarm scheme ensures the timely elimination of the freon leakage, which is one of the most important tasks among the malfunctions of the refrigeration units.

Timely detection and elimination will help to reduce emissions, which will have a positive impact on the ecosystem.

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LLMs as Cognitive Partners in Shipping 4.0: An Extend AI Approach to Maritime Predictive Maintenance Training

Tsigkris, N. [1], Sklavounou, E. [1], Tseles, D.[1] Papachristos, D. [2]*, Nikitakos, N.[3], Gegenava, A.[4], Kakhidze, A.[4] and Gegenava, T.[4]

[1]Dept. Industrial Design and Production, Univ. of West Attica, Greece

[2] Hellenic Navy Academy, Greece

[3] Dept. of Shipping, Trade & Transport, Univ. of Aegean, Greece

[4] Navigation Faculty, Batumi State Maritime Academy, Georgia

* Corresponding author: dimpap2009@gmail.com;

Abstract. This paper explores the integration of Generative AI (Gen AI) and Explainable AI (XAI) into Predictive Maintenance (PdM) within the Shipping 4.0 framework for educational use. The authors propose a conceptual framework called IPMDP (Intelligent Predictive Maintenance Decision Process for Education), which involves an architectural approach (System-of-System, SoS) for integrating LLMs (Gen AI approach) into the predictive maintenance of marine engines and systems, in order to support decision-making in the maintenance of systems at sea. The central idea of the conceptual framework lies in the utilization of a decision-making model using Gen AI techniques through the ExtendAI framework, which functions as a "cognitive partner" to a ship's engine room crew. The ultimate goal is the educational use of such a framework in the training of Merchant Marine engineers and other ship engine room personnel. Essentially, this study is a conceptual framework paper, integrating existing models and literature to propose a novel application domain, rather than presenting original empirical findings. This cognitive maintenance approach improves operational safety and ensures human-centric, accountable decision-making, which is crucial for regulatory compliance and effective adoption in the maritime industry.

Key Words: AI, Gen AI, PdM, Shipping Maintenance, XAI.

1. Introduction.

The global industrial landscape is currently undergoing a transformative period known as the "Fourth Industrial Revolution" or Industry 4.0 (I4.0). This era is defined by the digitization of traditional processes, effectively bridging the physical and virtual worlds through the deployment of cyber-physical systems (CPS), the Internet of Things (IoT), and Artificial Intelligence (AI). Within this context, the maritime sector is evolving toward "Shipping 4.0," a framework aimed at creating smart, interconnected, and autonomous industrial systems.

Developments in genetic artificial intelligence (GenAI), such as large language models (LLMs), generative adversarial networks (GANs), and diffusion models, are finding significant applications, including in the field of industrial maintenance, such as the PdM sector. As highlighted in the literature, GenAI offers a range of new capabilities, such as synthetic data generation, human-AI interaction through the use of natural language, and multimodal data analysis, thereby addressing long-standing challenges and creating new fields of application. Particularly in the shipping sector, the application of GenAI for PdM remains in its early stages, although there are constantly new efforts to implement it. A critical gap identified is the lack of an established standard for integrating it not merely as a recommendation engine but as a cognitive partner, a mechanism that respects the expertise of marine engineers, provides explainable results, and is suitable for educational use in training future merchant marine personnel (Li et al. 2026; Gan et al. 2023; Reicherts et al. 2025).

To address the gaps identified in the literature, this paper proposes a conceptual framework for maritime education called IPMDP-MME (Intelligent Predictive Maintenance Decision Process for Merchant Marine Education). The framework adopts a System-of-System (SoS) architectural approach to integrate GenAI, Explainable AI (XAI) & PdM in shipboard engine room personnel training. The central methodological innovation lies in the adoption of the ExtendAI decision-making model (Reicherts et al., 2025), where an LLM acts as a "cognitive partner" assisting the reasoning process rather than providing direct recommendations (RecommendAI). Unlike conventional systems, the adoption of the ExtendAI model offers the learner the ability to first formulate his own hypothesis, through which the system provides local suggestions, reflective questions and XAI-verified technical justifications based on real sensor data and knowledge graphs (KGs). This approach is the most pedagogically optimal approach so that the final maintenance decision remains under human control, while enhancing the cognitive ability of the user-learner. Furthermore, the use of the proposed framework in the educational practice provides advantages in terms of learning outcomes as well as operational security.

The structure of this paper is organized as follows: *Section 2* presents a literature review covering maintenance strategies, PdM in shipping, GenAI applications in maintenance, AI-assisted decision-making models, and the role of LLMs in education, *Section 3* discusses the adoption of Explainable AI (XAI) as a critical parameter for trust and accountability in maritime PdM, **S***ection 4* details the proposed IPMDP-MME conceptual framework, including its SoS architecture, and a step-by-step methodological roadmap. Finally, *Section 5* concludes a summary of findings, limitations, and future research directions.

2. Literature Review

2.1 Maintenance, PdM & AI in Shipping Sector

Maintenance plays an important role in the industrial sector, as its costs can account for a significant percentage of a company's total production costs (Bevilacqua and Braglia, 2000). Effective maintenance strategies prevent unexpected production interruptions, reduce costs, and can even increase the useful life of industrial machinery. For these reasons, maintenance approaches have undergone transformations as a result of the concerns and efforts of researchers, engineers, technicians, and specialists. Figure 1 illustrates this evolution over time (Nunes et al., 2023). Furthermore, maintenance approaches in industries are changing in response to the higher risks posed by complex equipment, greater demand for production, and the need to keep costs as low as possible. Over time, thinking about maintenance has focused mainly on three basic ideas: *reacting to problems, working to prevent them, and using predictions*.

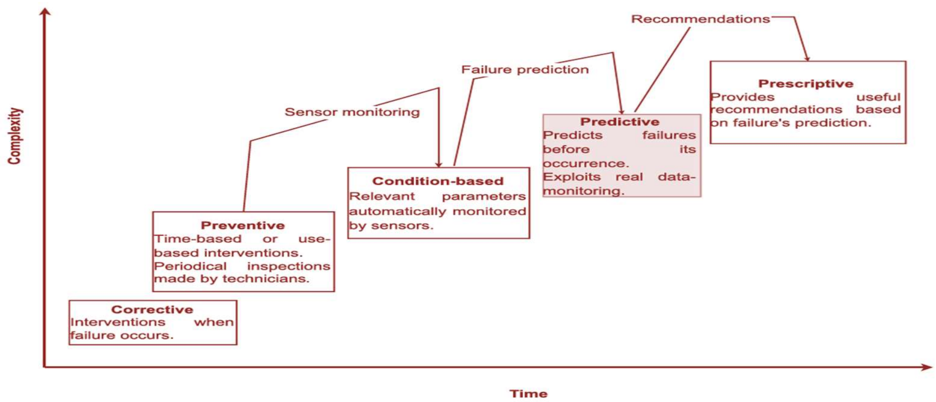

Figure 1. Historical Development of Maintenance Strategies (Nunes et al. 2023)

Maintenance strategies have evolved from a basic reactive model to more sophisticated proactive ones. The most elementary approach is Corrective Maintenance (CM), also known as "run-to-failure," where repairs are only made after a component has failed and disrupted equipment functionality. Driven by the high cost of unscheduled downtime, the field progressed to proactive strategies, beginning with Preventive Maintenance (PM). PM aims to prevent failures through regularly scheduled inspections by specialists and the replacement of parts based on fixed time intervals or a set number of operational cycles, as per manufacturer guidelines. However, this schedule-driven nature can result in two suboptimal outcomes: the premature replacement of components that still have substantial service life, leading to increased material costs (Mobley, 2002), or the unexpected failure of a part before its scheduled maintenance, requiring a costly emergency CM action that may have severe operational consequences (Hao et al., 2010).

The integration of Industry 4.0 and the Internet of Things (IoT) has shifted maintenance from scheduled approaches to Condition-Based Maintenance (CBM), which uses smart sensors to monitor equipment in real-time and trigger actions when parameters deviate from normal. As an evolution of CBM, Predictive Maintenance (PdM) employs Cyber-Physical Systems (CPS), Big Data, and artificial intelligence (AI) to forecast failures and estimate a component's Remaining Useful Life (RUL)(Table 1). This enables optimized, dynamic maintenance planning. Thus, PdM performs maintenance only when needed, making it highly economical. It relies on continuous monitoring and AI-driven analysis of historical and real-time data (using machine learning, statistical inference, and industrial indicators) to diagnose future failures and determine the optimal time for intervention. This field is competitively driven, with manufacturers striving to perfect these technologies (Bagheri et al., 2015).

Table 1. PdM Characteristics.

Description	
Key points	- The operational state of machinery is evaluated through the analysis of key indicators, including vibration, temperature, and acoustic measurements. - By predicting the likelihood of future equipment failures, PdM solutions facilitate maintenance actions at the most opportune moment. - The application of machine learning and analytics provides maintenance personnel with valuable, implementable information.
Advantages	- Minimized production downtime: Early detection of irregularities significantly lowers the risk of catastrophic equipment breakdowns. - Appropriate maintenance interventions extend the operational lifespan and preserve the functionality of machinery. - Optimized maintenance costs: Conducting solely essential servicing activities leads to more effective resource allocation. - Avoidance of accidents and environmental mishaps is made possible by predicting problems. - Contemporary Predictive Maintenance (PdM) minimizes waste generation and energy consumption by optimizing asset performance.

The shipping industry encompasses numerous activities, which are expected to undergo significant changes in the coming years as a result of technological developments and, in particular, the widespread expansion of AI use. According to the Organisation for Economic Co-operation and Development (OECD) report "*The Ocean Economy in 2030*", shipping industries will double their contribution to global value creation by 2030, due to the ongoing need for maritime trade. However, these estimates are directly influenced by the effective adoption of new technological innovations introduced under Industry 4.0 and inextricably linked to the framework of Shipping 4.0. Industry 4.0, as a consequence of the fourth industrial revolution, is expected to pave the way for smart, interoperable, and fully autonomous industrial systems in real time. This vision is based on the convergence of information and communication technologies, combined with cyber-physical systems (CPS), the Internet of Things (IoT), and cloud computing (CC) (Trakadas et al., 2019; Mahale et al., 2025).

Ship maintenance is a critical link in the chain of ship operations, ensuring their continued functionality, efficiency, and safety. However, it is also one of the biggest cost factors for shipping companies, accounting for 20% to 30% of a ship's total operating expenses (OPEX). In addition, this cost is directly linked to prolonged periods of downtime, resulting in reduced operational availability and financial returns. Predictive Maintenance (PdM) in shipping aims to proactively forecast equipment failures by analyzing real-time sensor data (e.g., from engine vibration and temperature). This data-driven approach identifies patterns that indicate when maintenance is truly needed, optimizing scheduling, minimizing both planned and unplanned downtime, reducing costs, and eliminating unnecessary tasks. As part of Shipping 4.0, PdM is expected to replace traditional strategies by enabling early detection of machinery issues. Despite this need, predictive approaches for ship reliability remain under-explored. This gap is critical, as studies show machinery damage (e.g., engine failure) was the leading cause of maritime accidents from 2009 to 2018, accounting for over a third of incidents, underscoring the urgency for predictive solutions (Kalafatelis et al., 2024; Aiello et al., 2019).

Thus, notable instances of machine failure incidents are prevalent within the maritime industry, highlighting the pressing need for proactive PdM strategies. In recent years, several publications in the international literature have analyzed different aspects of the diagnosis and prognosis of PdM-related faults. For example, several articles emphasize fault diagnosis for various ship subsystems e.g., battery system assessment for their Remaining Useful Life (RUL) and State of Health, and corrosion detection in marine structures (e.g., ship hull)(Kalafatelis et al., 2024).

Several key reviews exist in the field of Vessel Prognostics and Health Management (VPHM). These include overviews of methods for forecasting equipment lifespan (Remaining Useful Life), systematic comparisons of maintenance strategies (from Reactive to Predictive), and examinations of the role of classification societies in setting standards. While these studies provide a solid foundation for understanding VPHM, they leave a specific research gap unaddressed. The existing literature has not adequately explored the challenges and limitations in current real-world implementations of Artificial Intelligence (AI), particularly issues related to data transmission and privacy (Karatuğet al., 2023; Liang et al., 2024).

The next table shows a recent summary of AI methods in ship maintenance (Kalafatelis et al., 2024).

Table 2. AI Methods in Ship Maintenance.

Category of Methods	Indicative Models	Field of Application	Main Benefits
Statistics / Linear models	Ordinary Least Squares (OLS), LASSO, Polynomial Regression, Exponentially Weighted Moving Average (EWMA)	Fuel consumption prediction, Exhaust Gas Temperature (EGT) monitoring etc.	Simplicity, interpretability, low resource requirements
Kernel-based models	SVR, Kernel Ridge Regression (KRLS), Relevance Vector Machines (RVM)	RUL batteries, propulsion decay etc.	High accuracy in nonlinear systems
Tree-based models	Random Forest, Bagging, Gradient Boosting, XGBoost	Fault diagnosis piston rings etc.	Robustness, resilience in Noise & disturbances
Neural Networks (NN) & Deep Learning (DL)	FNN, DNN, CNN, DBN, Autoencoder, GAN	Fault classification, RUL prediction, EGT forecasting	High accuracy, complex learning capability
LSTM / Sequence Models	LSTM, Gated Recurrent Unit (GRU), Nonlinear Autoregressive Network with Exogenous Inputs (NARX), Weibull-Time-to-Event (WTTE)- Recurrent Neural Network (RNN)	Time-series prediction, RUL etc.	Holistic understanding of dynamic systems
Digital Twins (DT)	Hybrid DT-ML models	Hull/propeller fouling, speed loss, maintenance scheduling	Real-time optimization & simulation
Federated Learning	Federated Averaging (FedAvg), Asynchronous FL	FL-based PdM in Fleets	Privacy, lower bandwidth, collaborative learning

2.2 Gen AI in Maintenance

The introduction of Artificial Intelligence (AI) offers significant prospects for Predictive Maintenance (PdM), as it can detect potential issues (anomalies) within sensor data. This is why it has been the subject of extensive research activity. For instance, Wang et al. (2018) examined how deep learning supports various levels of analytical processing, from fault diagnosis to corrective recommendations. In the relative literature, several review articles have highlighted the value of AI in PdM, while also pointing out challenges related to the selection and integration of models (Carvalho et al., 2019; Zonta et al., 2020; Zonta et al., 2022). Moreover, in industry, various AI applications have been developed for fault detection and maintenance optimisation (Li et al., 2026).

The emergence of Gen AI (Generative AI) in AI is considered a turning point in the history of AI, comparable to the invention of the internet or smartphones. Gen AI is already affecting dozens of sectors: from education and health to marketing and programming. It creates new opportunities but also challenges (issues of employment, misinformation, ethics). LLMs force us to reinterpret what "intelligence," "creativity," and "understanding" mean. Essentially, Gen AI & LLMs are leading to a radically transformative era that opens up new possibilities but also requires responsibility and a response to the new challenges that arise.

Gen AI encompasses various types; each tailored for specific tasks or forms of media generation. The following are some of the more well-known types: Generative Adversarial Networks (GANs), Transformer-based Models (TRMs), Variational Autoencoders (VAEs), and Diffusion models (DMs), to name a few (Sengar et al., 2024).

Generative AI (Gen AI) excels at solving complex real-world problems like as Predictive Maintenance (PdM). Specifically, The use of GenAI in industrial maintenance is expected to provide a future model of Predictive Maintenance (PdM) in which human operators, databases, and complex systems will be fully and seamlessly integrated, sensor data and maintenance records will be converted into interpretable, actionable knowledge, and a series of high-fidelity failure scenarios will be generated to overcome data gaps. The figure below illustrates the potential implications of GenAI in the field of PdM according to (Figure 2) (Li et al., 2026):

- Collaborative Diagnosis use GenAI tools (LLMs) to facilitate human-machine interactions (HMI);
- Instruction Generation utilizes GenAI tools (LLMs) to create task-specific maintenance guidance;
- KG-Augmented PdM integrates GenAI with domain-specific KGs to apply existing knowledge bases in PdM; and
- Data Augmentation employs image generative models to synthesize diverse, high-fidelity failure data.

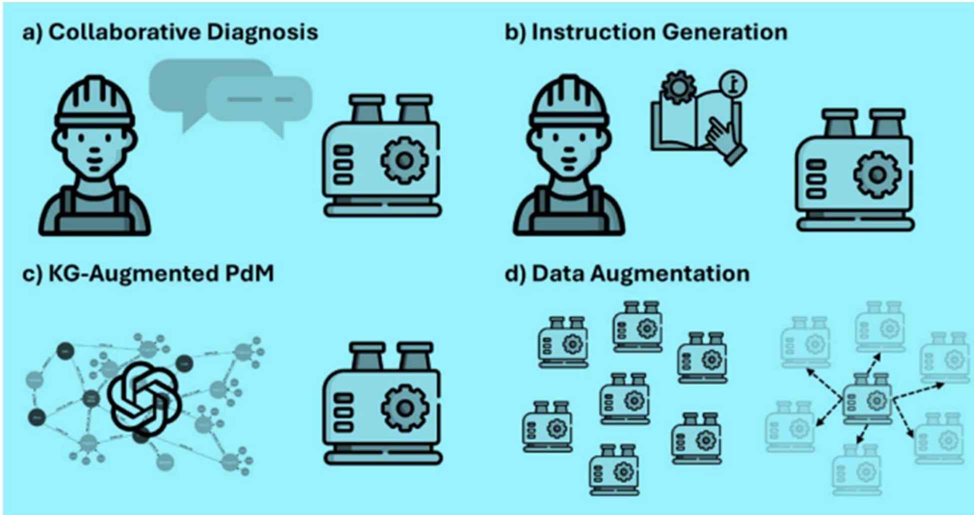

Figure 2. Envisioned Impacts of GenAI on PdM (Li et al., 2026)

The following table summarises the application of GenAI to PdM, where LLMs appear to be particularly effective for PdM tasks that require reasoning ability and text processing, aiming to improve information retrieval, generate domain Knowledge Graphs (KGs), and produce context-aware instructions across a wide range of industrial applications (robots, gearboxes, control systems etc.).

Table 3. Summary of GenAI of PdM applications (Li et al., 2026).

Models	Training	Impact
LLM	PT, FT	Collaborative Diagnosis
LLM	PT, FT	Instruction Generation
LLM	PT, FT	KG-Augmented Diagnosis
VAE	TfS	Data Augmentation
GAN	TfS	Data Augmentation
DM	TfS	Data Augmentation

Note: PT=Prompt tuning, FT=Fine-tuning, TfS=Training from scratch

GenAI (with LLMs) acts as an intelligent intermediary—capturing the domain knowledge from heterogeneous data and human expertise while augmenting the insights from limited historical records, ultimately delivering transparent, timely, and context-aware decision support. Thus, it won't be long before we see a PdM model in which operators, relevant knowledge bases, historical databases, and real-time machine signals are seamlessly integrated with the help of intuitive interfaces (Li et al., 2026).

2.3 AI-Assisted Decision Making in Maintenance

Decision-support tools (DS tool) that utilize AI are designed to work in collaboration with humans with the aim of optimizing performance beyond the limitations of either the human - or AI as the sole decision-making tool. This is referred to as human-AI complementarity (Bansal et al., 2021). Human decision-making is considered a fundamental cognitive function of the brain. Essentially, Decision-making is an extremely complex process, with AI support tools varying significantly in terms of their service delivery context. Research on AI-assisted decision-making focuses primarily on the provision of recommendations generated by AI through model predictions (Bao et al. 2023; Lai et al., 2023). Users must then evaluate and consequently accept or reject the machine's recommendation.

The emergence of GenAI and LLMs is enhancing productivity across various areas of human activity (e.g., software development). However, their use in decision-making presents a host of challenges and limitations, such as (Reicherts et al., 2025):

- Human factor superiority: In complex fields (e.g., investment management), humans perform better than AI tools, despite the vast amount of data that AI processes.
- Human skills: Human judgment, experience, and intuition are still considered decisive factors in decision-making.

Therefore, AI is not yet a universal solution ("panacea"). Any success it achieves depends on the context of its application and requires continuous evaluation and adaptation. However, AI, through GenAI and LLMs, is evolving from a simple tool into a "cognitive partner" that actively engages in reasoning, with two key interaction models, as identified by research (Figure 3)(Reicherts et al., 2025):

1. RecommendAI (Recommendation-centric AI)

   Function: The system analyzes data and directly suggests a ready-made final solution or course of action.

   Mode of thinking: It leads the user into backward reasoning, where they are merely called upon to evaluate and verify the pre-packaged proposal.

   Challenges: It reduces effort but carries the risk of diminished engagement and blind or excessive overreliance, even by experts.

   Countermeasure: Adding explanations or model confidence thresholds has limited success, as people often do not mentally process such information, while models may err with high certainty.

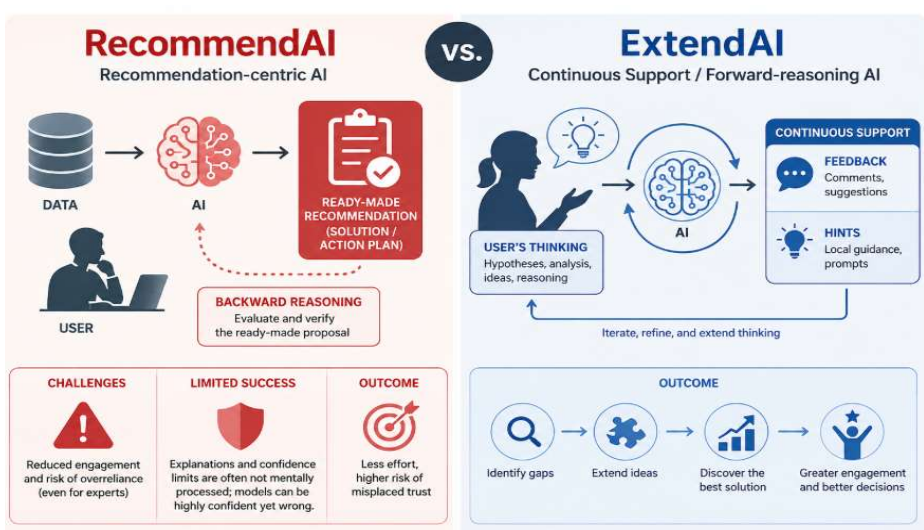

Figure 3. Decision-making models (Reicherts et al., 2025)

2. Extend AI (Continuous Support / Forward-reasoning AI)
   Function: It starts from the user's own reasoning (human-centric approach). The human first articulates their hypotheses or analysis.
   Mode of thinking: It acts as an extension of human reasoning lika a "partner."
   Outcome: Instead of a ready-made solution, the system offers feedback and localized hints, helping the user identify gaps, expand their ideas, and discover the optimal solution on their own.

2.4 LLMs in Education

In recent years, LLMs have represented a significant innovation. For example, OpenAI's GPT series, as well as Google Gemini and Anthropic Claude models, have had a profound impact on the field of AI thanks to their powerful capabilities regarding text generation and comprehension. In the field of education, their introduction is gradually transforming traditional teaching methods and driving innovation in educational technology. Specifically, the rise of GenAI over the last five years, and especially of LLMs as a result of advances in Deep Learning, has led to significant applications in the field of education. In particular, LLMs address key challenges of modern education by offering real-time feedback, reducing educational barriers, and enhancing personalized learning (promoting the Education 4.0 framework). Overall, they demonstrate significant results with continuously expanding prospects. In the near future, they are expected to become a central tool for transforming the educational system toward smarter and more personalized learning (Shang, 2025).

With the continuous development and optimization of LLM technology, it is expected that they will become smarter, capable of understanding and adapting to the personalized learning needs of different learners, and providing more accurate and effective learning support. On the other hand, the spread and development of educational technology may significantly narrow the educational gap between urban and rural areas, and offer more people opportunities for high-quality education. In the future, education may not only involve interaction between teachers and students as individuals, but also collaborative learning between humans and an artificial intelligence model (in the case of LLMs). In this case, teachers transform into learning guides, cultivators of critical thinking, and agents of ethical and humanistic care. As an integral part of education, LLMs will offer learners personalized learning programs. At the same time, those in charge of the respective educational systems must maintain constant attention and reflection regarding humanitarian and ethical issues (Shang, 2025; Gan et al., 2023).

Consequently, the education sector has begun to explore how to integrate LLMs with education to enhance teaching quality and effectiveness. The following Figure illustrates the importance of introducing LLMs and the current practical areas in Education:

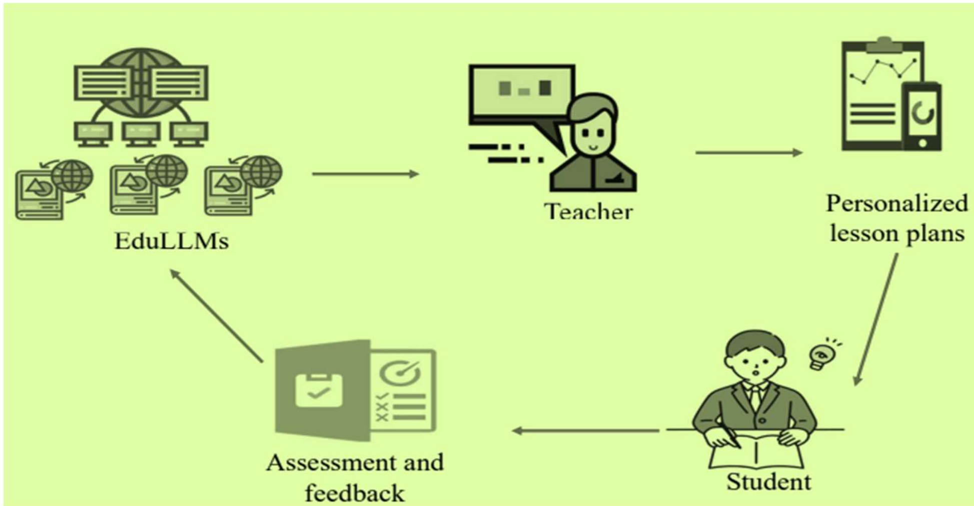

Figure 4. Architecture of LLMs for education (Gan et al., 2025)

In maritime training, AI is being used more and more, particularly in simulator-based training. Related research examines potential anomalies in simulation log data to identify discrepancies in trainee performance. At the same time, eye-tracking technology is used to analyze visual attention, comparing experienced and inexperienced officers via heatmaps, in order to improve electronic navigation skills. Furthermore, AI-powered speech analysis enhances maritime training by combining advanced language models and voice recognition techniques, enabling more precise communication in high-pressure and stressful environments. Finally, another important area of application is the analysis of cognitive load and stress, where biometric indicators such as pupil diameter, electrodermal activity, and heart rate are used to assess the impact of stress on trainee performance during maritime scenarios conducted in maritime simulators (Munim and Kim, 2023; Xue et al., 2024).

3. Adoption Explainable AI- XAI and PdM in Shipping

In the context of the transition to Shipping 4.0, Explainable Artificial Intelligence (XAI) is emerging as a critical factor for the acceptance of Generative AI (Gen AI) models in ship maintenance. While traditional deep learning models (such as GANs and VAEs) offer high accuracy, they often function as black boxes, making it difficult for engineers to understand the logic behind a prediction failure.

One of the most critical challenges for the adoption of Generative AI (Gen AI) in maritime operations is the “black-box” nature that characterizes complex models such as GANs and VAEs. Although these systems demonstrate exceptional accuracy in anomaly detection, their inability to explain the reasoning behind a specific failure prediction creates trust gaps between the system and the ship’s engineers. In the context of Maritime 4.0, where an incorrect diagnosis in critical equipment can lead to costly delays or safety risks, research into Explainable AI (XAI) methods becomes imperative.

The integration of XAI techniques enables the transformation of abstract predictions into understandable technical justifications, for example by linking a detected deviation in vibration patterns to the specific degradation of a bearing. Moreover, the use of XAI functions as a safeguard against LLM “hallucinations,” allowing the crew to verify the generated maintenance recommendations based on actual sensor data and manufacturer manuals. In this way, AI ceases to be an isolated tool and is transformed into a reliable troubleshooting copilot, ensuring that decision-making remains under human control.

The integration of XAI can be analyzed through the following axes (Adadi and Berrada, 2018; Arrieta et al., 2020; Gunning and Aha, 2019):

A.Trust Building

- Ship engineers and crew demand transparency and justification for diagnoses concerning critical equipment, such as main engines and generators.
- Research into XAI methods is essential to understand the rationale behind model predictions, thereby strengthening human trust in the system.
- Without explainability, the adoption of advanced PdM systems remains limited due to users' reluctance to rely on unverifiable decisions.

B.Addressing "Hallucinations"

- Large Language Models (LLMs), if not properly fine-tuned, can produce inaccurate content or incorrect diagnoses.
- XAI allows these "hallucinations" to be identified, ensuring that automatically generated maintenance instructions are based on actual data and technical manuals.

C. Improving Decision Making

- Explainable AI transforms sensor data (vibration, temperature) into understandable information, allowing the crew to act proactively.
- By linking the anomalies detected by VAEs to specific operating parameters, XAI helps determine the exact cause of an impending failure.

D. Integrating into the PdM Roadmap

- The implementation of XAI is the connecting link between Failure Diagnosis and Mitigation in the predictive maintenance pyramid.
- It allows systems to act as a "troubleshooting copilot", providing not only the prediction but also the "why" behind the proposed maintenance action.
- The table (Tab.4) below highlights the added value of XAI for decision-making by the crew (Human-in-the-loop).

Table 4. Comparative Analysis between Traditional AI and Explainable AI (XAI) in Maritime Maintenance.

Feature	Traditional AI (Black-Box)	Explainable AI (XAI / Glass-Box)
Output Type	Provides only the prediction (e.g., "Failure Probability: 85%")	Provides prediction accompanied by rationale (e.g., "Due to thermal deviation in Bearing X")
Transparency	Low/Opaque. Internal processes and decision logic are hidden	High. Utilizes interpretability methods (e.g., SHAP, LIME) to highlight key features
User Trust	Limited. Engineers may hesitate to intervene without technical justification	High. Engineers understand the "why," leading to confident and timely actions
Error Management	Difficult to identify the root cause of a false positive/negative	Streamlined identification and mitigation of model bias or data drifts
Regulatory Compliance	Challenges in meeting safety standards and Class society requirements	Facilitates certification through traceability and accountability of AI decisions

3.1 Integrating XAI into the PdM Roadmap: Bridging the "Black-Box" Gap

To successfully transition from traditional Predictive Maintenance to *Cognitive Maintenance,* Explainable AI (XAI) must be integrated as a strategic layer within the existing PdM framework. In the proposed roadmap, XAI acts as the critical bridge between algorithmic output and human action:

- *Stage I: Anomaly Detection:* Gen AI models (e.g., VAEs) monitor normal operational behavior and identify deviations.
- Stage *II: Failure Diagnosis & The XAI Layer:* This is where the "Black-Box" is opened. XAI techniques translate complex neural network weights into human-understandable technical justifications (e.g., attributing a vibration spike to specific piston wear).
- *Stage III: Degradation Prognosis:* By understanding the *why* behind a diagnosis, the prediction of Remaining Useful Life (RUL) becomes more reliable for the Chief Engineer.
- *Stage IV: Mitigation & Decision Support:* LLMs acting as "troubleshooting copilots" use the XAI-verified data to generate precise maintenance actions, reducing the risk of "hallucinations".

3.2 Ensuring Accountability through Explainable AI (XAI)

As the maritime industry transitions toward *Shipping 4.0*, the deployment of Generative AI (Gen AI) in maintenance operations introduces a critical requirement for Autonomy. While traditional deep learning models, such as Variational Autoencoders (VAEs) and Generative Adversarial Networks (GANs), offer high accuracy in detecting engine anomalies, they often operate as "black-box" systems. This lack of transparency poses a significant barrier to adoption, as ship engineers require a clear understanding of *why* a specific failure prediction was made before initiating costly or mission-critical repairs.

To address this, the integration of *Explainable AI (XAI)* serves as a vital bridge between algorithmic output and human decision-making. By utilizing interpretability methods such as SHAP (SHapley Additive exPlanations) or LIME (Local Interpretable Model-agnostic Explanations), the system can translate complex sensor deviations into actionable technical justifications (e.g., attributing a vibration spike to specific piston ring wear). Furthermore, XAI plays a crucial role in mitigating the risks associated with *AI hallucinations*—instances where Large Language Models (LLMs) might generate inaccurate maintenance instructions. By providing a traceable rationale for every diagnosis, XAI ensures that the "troubleshooting copilot" remains a reliable tool for the crew. This transparency not only builds trust among shipboard personnel but also facilitates compliance with stringent international safety regulations and classification society standards

4. The Proposed Conceptual Framework (IPMDP-MME)

The proposed framework is based an Intelligent Predictive Maintenance Decision Process integrating GenAI, XAI and PdM for the educational training of Merchant Marine engineers (IPMDP-MME). The baseline of proposed framework defines the system as a GenAI/XAI-supported PdM framework for marine engines and engine-room systems, with ExtendAI acting as a "cognitive partner" rather than a replacement for the Marine engineer's judgement. The main pillars of the proposed framework are (Adadi and Berrada, 2018; Arrieta et al., 2020; Gunning and Aha, 2019; Reicherts et al., 2025; Li et al., 2026; Sengar et al., 2024; Munim and Kim, 2023):

- *Human-Centric Approach*: The trainee first formulates their own hypotheses about a fault, acting as the primary decision-maker.
- *Cognitive Partner*: GenAI does not provide ready-made solutions but expands the user's thinking through feedback and local hints.
- *Explainability (XAI Layer*): Every suggestion/recommendation from the system is documented based on real sensor data and technical manuals, avoiding hallucinations.

The system should be implemented as a *human-in-the-loop educational decision-support System-of-System* **(***SoS)*, not as an maintenance decision-maker without human implication. The trainee remains responsible for the final diagnosis and maintenance plan, while the GenAI provides traceable, evidence-based support. This is consistent with the article's emphasis on accountable, human-centric cognitive maintenance and with the ExtendAI evidence that reasoning-extension integrates better with the user's decision process than direct recommendation.

The architecture of proposed conceptual framework follows the System-of-Systems (SoS) approach (system Engineering methodology) for the integration of heterogeneous technological entities. The systems comprising the SoS are:

- *Data Acquisition System***:** Collects real-time data (e.g., vibrations and temperatures) from the ship's machinery.
- *Knowledge Base System***:** Includes manufacturers' technical manuals and maintenance history records, organized through Knowledge Graphs (KGs).
- *ExtendAI Core (LLM):* The "brain" of the system, which receives the user's reasoning process and interprets it through Retrieval-Augmented Generation (RAG).
- *XAI Interface***:** Visualizes the reasoning behind each recommendation (e.g., through SHAP or LIME) in order to establish trust.

For example, to ensure that the system operates as an ExtendAI model rather than as a RecommendAI system, the following prompt is proposed:

ROLE: "Act as a Cognitive Partner for a Merchant Marine Engineer within a Predictive Maintenance (PdM) environment.

Your mission: Do not provide direct diagnoses or ready-made solutions.

Process:

1. Wait for the trainee to express their initial analysis or fault hypothesis.
2. Analyze the trainee's reasoning and identify gaps based on sensor data (e.g., exhaust gas temperature) and technical manuals.
3. Provide local hints and reflective questions that encourage deeper reasoning (e.g., 'Did you consider the deviation in lubrication pressure?').
4. Every response must be accompanied by technical justification (XAI) in order to minimize hallucinations and ensure transparency.

The GOAL is for the learner to discover the best course of action on their own.

In addition, the next table (Tab.5) shows a use case for Merchant Marine Engineers in a Main Engine Failure.

Table 5. Use Case: Training Merchant Marine Engineers in a Main Engine Failure Scenario.

Scenario	The trainee observes abnormal vibrations in a Main Engine bearing through the simulator environment
User Action	The trainee enters the following assumption into the system: "I believe there is bearing shell wear due to excessive temperature."
ExtendAI Response	The system does not respond with a direct recommendation such as, "Yes, replace the bearing shell." Instead, it replies: "Your assumption regarding the temperature is valid. However, observe the vibration spectrum at frequency X. How does this relate to the lubrication condition?"
Outcome	The trainee reviews the XAI visualizations, correlates the available data, and ultimately reaches a more comprehensive and holistic diagnosis independently

The methodological approach adopted for the transition toward Cognitive Maintenance follows four (4) sequential stages:

- *Stage I: Anomaly Detection*. Utilization of GenAI models (e.g., Variational Autoencoders – VAEs) for the identification of deviations from normal operational conditions.
- *Stage II: Failure Diagnosis & XAI Layer*. Transformation of "black-box" predictions into interpretable technical justifications through Explainable AI mechanisms.
- *Stage III: Degradation Prognosis*. Estimation of the Remaining Useful Life (RUL) based on the validated and explainable diagnostic outcomes.
- *Stage IV: Mitigation & Decision Support*. The trainee, supported by GenAI (LLM) acting as a cognitive "copilot," makes the final maintenance decision regarding the appropriate corrective or preventive action.

IPMDP-MME prioritizes the user's initial reasoning, providing feedback and local hints to guide the learner toward discovering the optimal maintenance path. The system operates in a *Forward-Reasoning* loop:

1. *Human Initiation*: The trainee observes an anomaly and proposes an initial hypothesis (e.g., "Vibration indicates bearing wear").
2. *System Verification*: The ExtendAI engine checks the hypothesis against the *Ship Sensor Node* and *Knowledge Graph*.
3. *Cognitive Extension*: Instead of confirming/denying, the system provides a "Local Hint" (e.g., "Check the lubrication pressure trend before concluding").
4. *Accountable Decision*: The trainee refines their reasoning based on hints and XAI data to reach the final maintenance decision

Also, the following table describes the core nodes of the SoS architecture and their functional roles in the predictive maintenance process:

Table 6. Comparative Analysis between Traditional AI and Explainable AI (XAI) in Maritime Maintenance.

SoS Node	Function Description	Data Interaction
Ship Sensor Node	Real-time data acquisition from marine engines (vibration, temp, pressure).	Streamed to the Analysis Engine.
Knowledge Graph (KG)	Structured repository of technical manuals and historical maintenance logs.	Provides context for RAG.
ExtendAI Engine (LLM)	The cognitive core that evaluates human reasoning against sensor data.	Processes User Inputs + KG context.
XAI Layer	Translates complex AI outputs into human-understandable technical justifications.	Outputs technical evidence for hints.

Finally, the following diagram illustrates the hierarchical relationship between the various systems (SoS), with the user (trainee engineer) and the “cognitive partner” GenAI (LLM) playing central roles. This structure ensures that the educational process remains human-centered, with artificial intelligence serving to augment human thought rather than replace it. More specific, in Figure 5 shows:

- User Interface (UI) / Cognitive Extension Loop: represents the user’s thought process (“User’s Reasoning & Hypothesis”) and initiates the continuous interaction loop (learner-user & AI system/LLM).
- AI & Knowledge Core: The central control core, where the ExtendAI Engine (LLM) processes the user’s input, using Retrieval-Augmented Generation (RAG) to access external knowledge, while the Explainable AI (XAI) Layer provides accurate (reliable, to the extent possible) technical documentation.
- Data Sources & Knowledge Base: The database and knowledge base are fed (RAG input) by information sources related to ship sensor data (Ship Sensor Node) and organized knowledge (Knowledge Graph, KG).

- Methodological Roadmap: At the bottom of the image, the four-stage methodology is visualized: Anomaly Detection, Failure Diagnosis & XAI, Degradation Prognosis (RUL), and Mitigation & Decision Support.

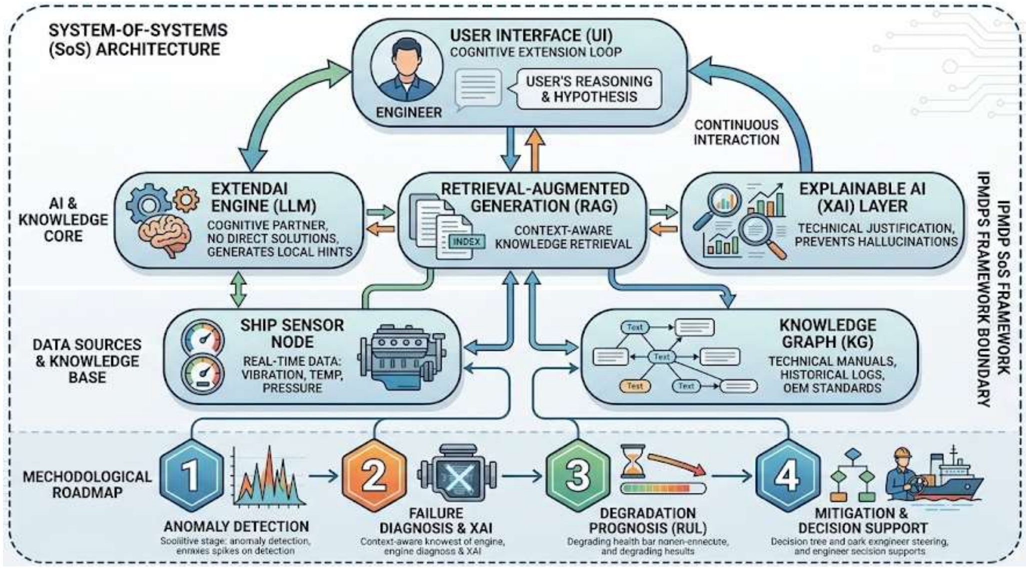

Figure 5. Conceptual framework IPMDP-MME Architecture (by authors)

5. Conclusions

The transition from traditional maintenance models to the Shipping 4.0 era represents a fundamental paradigm shift in maritime operations. It overcomes traditional AI's data scarcity by generating synthetic data for rare failures. In summary, while Gen AI offers transformative potential for the shipping industry, its successful deployment requires a balanced approach that addresses technical integration, data privacy, and the human-centric requirement of interpretability. Future research should focus on refining *Edge Computing* solutions to run these complex models within the resource-constrained environment of sea-going vessels.

As regard the IPMDP-MME the following arise:

- The integration of Explainable Artificial Intelligence (XAI) is critical to making predictions understandable and reliable. Additionally, the use of XAI in combination with Retrieval-Augmented Generation (RAG) from technical manuals and ship sensors is concluded as a necessary strategy to mitigate the inaccurate diagnoses produced by LLMs, ensuring that every indication is substantiated by real data.
- The main conclusion of the proposed IPMDP-MME framework is that Large Language Models (LLMs) should not function as direct recommendation systems (RecommendAI) that provide ready-made solutions. Instead, they should function as "extended intelligence" (ExtendAI), extending the user's reasoning through suggestions, while keeping the human in the central role of decision-making.

- The proposed framework (IPMDP-MME) appears to facilitate compliance with safety regulations and the requirements of classification societies (Class societies), as it provides traceability and accountability for every decision (XAI), while keeping the trainee-user responsible for the final action regarding the maintenance of a system or subsystem.

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Transforming Maritime SAR Operations: Towards a Theoretical Framework for Human-AI Collaboration

Papachristos, D.[1]*, Nikitakos, N. [2], Gegenava, A.[3], Kakhidze, A.[3], Gegenava, T.[3] and Kallou, S.[4]

[1]Hellenic Navy Academy, Greece

[2] Dept. of Shipping, Trade & Transport, University of Aegean, Greece

[3] Batumi State Maritime Academy, Georgia

[4] Dept. Port Management and Shipping, National and Kapodistrian University of Athens

* Corresponding author: dimpap2009@gmail.com;

Abstract. This paper examines how Generative AI and Large Language Models (LLMs) can support decision-making in Maritime Search and Rescue (MSAR) operations through a human-centered collaborative framework. The authors propose a theoretical Human-AI Deliberative Framework (HADF) based on the ExtendAI approach, into Maritime Rescue Coordination Centers. In this framework, the human operator first develops and explains an operational plan, after which the AI extends the reasoning by providing structured feedback, identifying cognitive gaps, and supporting reflection while keeping the final decision under human control. The model combines LLM interaction, optimization methods, and supporting datasets to enhance planning quality. Reported benefits include increased decision confidence and satisfaction, as well as improved reasoning depth, though at the cost of greater cognitive effort (the results are drawn from the main study Reicherts et al., not from primary data). Overall, the study argues that AI should function as a complementary reasoning partner, improving outcomes without replacing human judgment in critical MSAR operations.

Key Words: MSAR, Gen AI, LLM, Artificial Intelligence.

1. Introduction

In 1914, maritime nations convened to establish the first international framework for maritime safety (International Convention for the Safety of Life at Sea, SOLAS) following the Titanic disaster (1912). By 1959, the International Maritime Organization (IMO) assumed leadership, expanding the global mandate from basic accident prevention to the development of sophisticated emergency response frameworks.

Central to this modern infrastructure are the SAR Convention and the Global Maritime Distress and Safety System (GMDSS), the latter becoming fully operational in 1999. These systems leverage satellite and terrestrial telecommunications to ensure that both shore-based authorities and nearby vessels receive instantaneous distress alerts. This integrated approach facilitates rapid, coordinated search and rescue operations, significantly increasing survival rates during maritime emergencies.

The paper proposes utilizing the ExtendAI model, a Gen AI-LLM tool, within a Maritime Rescue Center (MRC) to integrate AI feedback into a user's decision-making process, aiming to enhance reasoning and improve SAR outcomes, despite requiring more cognitive effort from the user. Specifically, it proposes the use of Gen AI to complement and enhance the reasoning of the user performing MSAR operations, extending their initial plan through comprehensive feedback, with the aim of supporting reflection, identifying knowledge gaps, and improving decision-making outcomes, while keeping the user in ultimate control. Essentially, the present study is a conceptual framework paper, integrating existing models and literature to propose a novel application domain, rather than presenting original empirical findings.

2. Literature Review

2.1 Maritime Search and Rescue (MSAR)

Maritime Search and Rescue (MSAR) operations are critical humanitarian activities aimed at locating and assisting individuals in distress at sea. These operations are inherently complex, characterized by high uncertainty, dynamic environmental conditions, and significant resource constraints. The primary objective of any SAR action is the swift return of survivors to a place of safety (Laperrière-Robillard et al., 2025; Kilic et al., 2025).

The International Aeronautical and Maritime Search and Rescue (IAMSAR) manual outlines the standard operating procedures and hierarchical structure for MSAR. This framework typically involves five distinct stages (Figure 1) (ICAO-IMO, 2022):

- Awareness: This initial phase involves receiving a distress call and identifying the last known position (LKP) of the victim.
- Initial Action: This stage focuses on evaluating the distress call and making preliminary decisions, including identifying the On-Scene Coordinator (OSC) and gathering local meteorological and aeronautical data to calculate the probability of containment (PoC).
- Planning: This crucial stage is dedicated to formulating a response strategy, which includes conducting thorough risk assessments, determining necessary resources, identifying optimal entry points, and selecting the most effective search patterns.
- Operations (Execution): During this phase, the OSC directs the mission, utilizing sensors, updating sweep patterns, and coordinating with various agencies in real-time.
- Conclusion: Operations conclude when the distressed subjects are rescued, or it is determined that further efforts are unlikely to yield additional survivors.

Figure 1. IAMSAR MSAR Operational Stages – Block Diagram.

SAR mission coordinators (SMCs) are highly trained individuals responsible for the planning, coordination, control, and management of these operations (Laperrière-Robillard et al., 2025; Xu et al. 2011). Traditional MSAR (Maritime Search and Rescue) frameworks encounter several key challenges: the difficulty in pinpointing the initial incident location due to uncertain and imprecise data; the dynamic impact of changing weather, currents, and tides on survivor positions; limitations in available personnel, assets, and time; the need for continuous adaptation of plans based on new information; and structural rigidity within hierarchical, human-centered communication systems, which can cause slow adaptation to real-time changes, resulting in operational delays and the amplification of errors throughout the mission (Kilic et al., 2025).

2.2 Gen AI and LLMs

Artificial Intelligence (AI) is an overarching term encompassing computational algorithms capable of performing tasks that typically require human intelligence, such as understanding natural language, recognizing patterns, making decisions, and learning from experience. Machine Learning (ML) is a subfield of AI focused on algorithms that autonomously solve tasks through exposure to data without explicit programming. Deep Learning (DL), a more advanced subset of ML, utilizes artificial neural networks with multiple hidden layers to model complex data representations and automatically detect correlations and patterns in large datasets (Janiesch et al., 2021; Banh and Strobel, 2023).

The swift advancement of Generative AI has revolutionized the discipline, largely driven by architectures like the Generative Pre-trained Transformer (GPT) family. By utilizing immense neural networks, cutting-edge machine learning techniques, and colossal datasets for training, these systems have attained an exceptional ability to understand and generate text that closely mimics human language. The proliferation of open-source platforms and easy access to these tools have made powerful generative LLMs widely available, accelerating their deployment and application across a broad spectrum of industries such as conversational AI, medical services, and financial services.

In the early 2010s, Recurrent Neural Networks (RNNs) were effective for processing sequential data and generating coherent text, but they faced limitations such as difficulty capturing long-range dependencies, gradient instability, and slow computation. The introduction of transformer architectures marked a major shift by using attention mechanisms to analyze entire sequences simultaneously, enabling better context understanding, parallel processing, and improved handling of long-term dependencies. Models such as GPT surpassed RNNs through multi-headed self-attention and more advanced linguistic modeling. As transformer technology evolved, combined with larger datasets, increased computational power, and growing parameter sizes, Large Language Models (LLMs) rapidly advanced and became highly capable in complex natural language processing tasks. Today, LLMs are widely used across sectors including healthcare, finance, education, and technology. They support applications such as text generation, translation, summarization, and sentiment analysis; power chatbots and virtual assistants; assist in medical diagnosis and patient interaction; enhance financial operations through automated trading and fraud detection; enable personalized learning; and contribute to creative and technical fields through code generation, content creation, music composition, and visual art production (Gillioz et al., 2020).

2.3 Human-AI Collaboration

In the age of intelligent systems, core human interaction with technology is increasingly defined by partnerships with autonomous AI agents. This form of Human-AI collaboration (HAC) represents an emerging type of relationship, enabled by machines with independent decision-making capabilities. Within this framework, AI agents evolve beyond mere tools to become active teammates, working jointly with humans to achieve shared objectives. The human-centered AI (HCAI) approach reinforces the indispensable leadership role of humans within these teams. This human-led partnership adds new complexity to the traditional human-machine dynamic, demanding fresh research perspectives, methodologies, and priorities to tackle the distinct challenges inherent in HAC (Akata et al., 2024; Andrews et al., 2022). Furthermore, Human-AI collaboration (HAIC) refers to the synergistic interaction between human and AI agents working toward shared goals, where each party contributes unique capabilities to achieve outcomes superior to either working alone. This theoretical framework is grounded in several foundational concepts from cognitive science, human factors engineering, and information systems research (Seeber et al., 2020).

The integration of AI into decision-making processes represents a fundamental shift from traditional automation paradigms to collaborative human-machine systems. Unlike earlier automation that simply replaced human tasks, contemporary AI systems are designed to work alongside humans in complementary partnerships (Jarrahi, 2018). This collaborative approach is particularly critical in high-stakes domains such as maritime search and rescue (MSAR) operations, where the complexity of decision-making requires both human expertise and computational capabilities (Endsley, 2017).

3. Decision-Making Support for Maritime Search and Rescue Operations

The aim of this article is to explore decision-making support for planning maritime search and rescue (SAR) operations at a Maritime Rescue Center (MRC) with the help of Gen AI Tools. To plan the search operation, a likely starting point (datum) must be established. This calculation considers: the reported location and time of the incident, the delay until rescue vessels arrive, the surface drift of both the distressed and rescue vessels during that period, and the likelihood of a rescue aircraft reaching the site before the vessels (Figure 2).

When designing the search, it is also important for the surface search coordinator to determine the distances between approaching assisting vessels, their courses, and their speeds. These factors depend on the chosen search method, the maximum speed of the slowest vessel present, and the possibility of limited visibility in the search area. Furthermore, in addition to search and rescue planning, the evaluation and selection of assets available to the Maritime Rescue Center (MRC) for the specific search and rescue operation should also be included. Additionally, the international legal framework should be taken into account.

Figure 2. Search Area with datum

The ultimate goal of AI decision support tools is to work with hu mans to potentially reach the best performance that overcomes the limitations of either human or AI on their own **Error! Reference source not found.**. Decision-making is a highly complex process and AI support tools may vary profoundly in when, how, and what they provide. Research in AI-assisted decision-making largely focuses on providing AI-generated recommendations from model predictions **Error! Reference source not found.**. Users must then evaluate and consequently accept or reject the recommendation. Recommendations are either presented on their own or combined with additional AI support elements such as various types of model explanations or uncertainty. While sometimes successful in increasing accuracy and efficiency in generic or artificial tasks, AI-assisted decision-making has its challenges, including low user acceptance in more complex decision-making processes, and overreliance on (incorrect) AI recommendations (Wang and Yin, 2021; Reinchert et al., 2025).

On other hand, research on the use of LLMs for AI-assisted decision-making is still in its early stages, with the few existing studies mainly following three broad directions. The first is applying LLMs within the established paradigm of explainable AI. A second direction is the usage of LLMs to enrich AI recommendations with additional evidence that is related to the task rather than the AI model. Lastly, researchers have explored the use of LLMs for designing AI agents that can engage with users in various forms of discussions (Reinchert et al., 2025). Ma et al. (2024) on the other hand proposed the concept of Deliberative AI, where both the human and the AI first present their viewpoints. Afterwards, they deliberate on conflicting opinions and discuss individual features until a final decision is reached. Finally, the approach of Reicherts et al. **Error! Reference source not found.**, in which the user starts by presenting their own rationale and then receives the AI's perspective, but has more sophisticated procedures. That is, they propose that AI is extended and integrated into human reasoning, with the aim of engaging the user in a forward reasoning mode. Therefore, the user does not need to understand an independent perspective of AI (Figure 3).

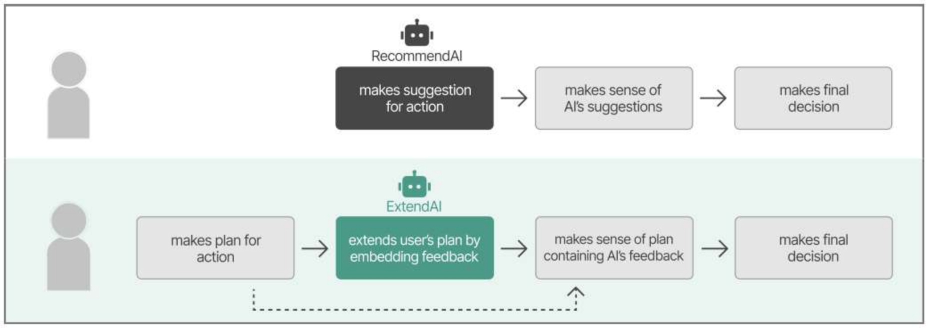

Figure 3. Illustrative comparison of the thought process when interacting with two 'types' of AI – RecommendAI and ExtendAI (Reinchert et al., 2025)

4. The Proposed Conceptual Framework

In MSAR case, we employ the ExtendAI model by Reicherts et al. (2025). In this model, the user "creates a plan for action" and then "articulates their reasoning" to the AI (a Gen AI-LLM tool). The AI (ExtendAI) then "extends the user's plan by integrating feedback." This augmented reasoning is returned to the user, with the AI's feedback highlighted (in bold), so that the user can see the AI's suggestions directly within the context of their original thoughts. The user then "understands the plan containing the AI's feedback" and "makes the final decision". The aim is to complement and enhance the user's reasoning processes by more closely integrating the AI into their decision-making workflow. It seeks to help users reflect and identify potential gaps in their reasoning. According to the research by Reicherts et al. (2025), the model was more effectively integrated into people's decision-making and personal thinking processes, leading to slightly better outcomes. It supported users in reflecting on their reasoning, resulting in more informed and improved decisions. Participants reported that it gave them more freedom to think independently and helped them to "think more deeply about their decisions," while also expressing greater satisfaction with their decisions (67%) and reporting higher confidence (76%) (these results are derived from the original study by Reicherts et al. (2025), not from primary data). However, it does require more cognitive effort from the user, as they must articulate their reasoning, and the process of writing out this reasoning may be perceived as "annoying" or "somewhat tiring". Similarly, the Figure 4 illustrates our adaptation of this model by incorporating the optimization algorithm presented in the study by Abi-Zeid et al. (2019), as well as a supporting material dataset that must be provided to the LLM to enable optimal decision support.

Thus, the core of proposed framework:

"The AI complements and enhances the user's reasoning by extending their initial plan through integrated feedback, aiming to support reflection, identify cognitive gaps, and improve decision-making outcomes while keeping the user in final control."

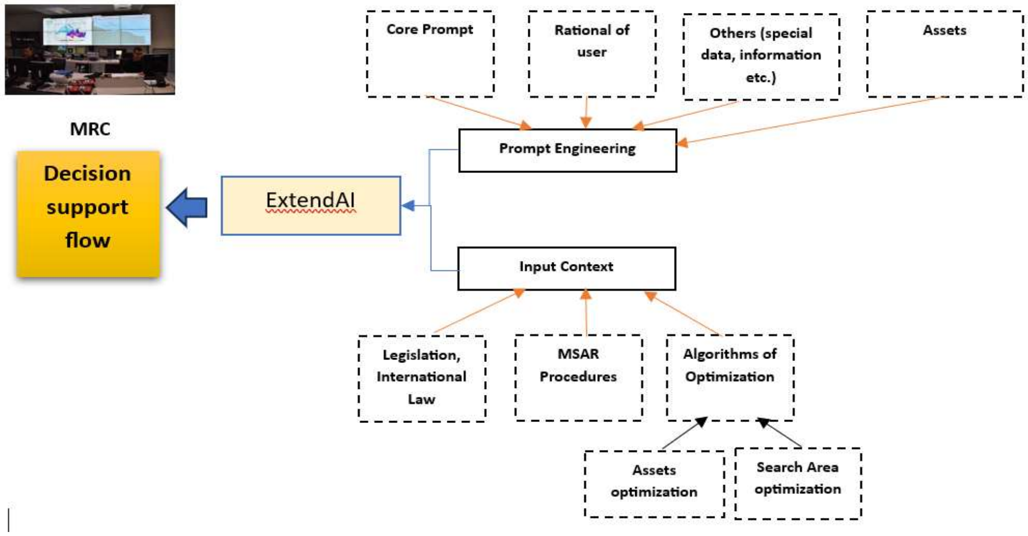

Figure 4. Decision Support process by using LLM for MSAR (by authors)

Specifically, the proposal follows a structured collaborative workflow between the user and the Gen AI (Table 1):

- *Articulation:* The user creates an action plan and articulates their reasoning to the AI.
- *Extension:* The Gen AI (ExtendAI model) analyzes the logic and provides highlighted feedback to fill gaps.
- *Integration:* The system incorporates an optimization algorithm and a specific supporting dataset to ensure high-fidelity decision support.
- *Final Decision:* The user reviews the augmented plan and retains ultimate authority over the final decision.

Table 1. Benefits vs. Challenges

Benefits	Challenges
76% increase in decision confidence.	Requires higher cognitive effort from the user
Identification of reasoning gaps.	The articulation process can be perceived as tiring.
67% higher satisfaction with outcomes.	Requires a robust dataset for optimal support

4.1 Case Study: Human-AI Deliberative Collaboration During a Maritime SAR Incident

Based on the Human-AI Deliberative Framework (HADF), a scenario of using the conceptual framework is presented. The scenario is hypothetical and designed to demonstrate the operation of the ExtendAI model in real time, without constituting primary research. The scenario highlights how the use of AI cannot and should not replace humans, but rather should function as an "external memory" and, at the same time, an "analytical controller," though it requires increased cognitive effort from the user to synthesize the necessary information. Specifically:

A. *Scenario Setup*

- *Incident:* A distress call is received from the 12-meter vessel "Blue Wave" reporting engine failure and water ingress.
- *Location:* 15 nautical miles Northwest of Ikaria.
- *Weather Conditions:* Northern winds at 6 Beaufort, heavy seas, and a water temperature of 18°C.
- *Available Assets*: 1 Coastal Patrol Boat (CPB), 1 Super Puma Helicopter, and 2 nearby commercial vessels.

B. *Step-by-Step HADF Implementation*

The process follows the standard IAMSAR stages, integrating the human-AI collaborative loop.

- Stage 1: *Awareness*. The SAR Mission Coordinator (SMC) receives the alert and logs the data into the system. AI Support: The system processes the coordinates and activates trajectory modeling to calculate the Initial Probability of Containment (PoC).
- Stage 2: *Initial Action*. The SMC classifies the incident as a "Distress Phase," requiring immediate intervention. Human Input: The SMC prioritizes the immediate launch of the helicopter to maximize the "golden hour" for survival.
- Stage 3: *Planning / ExtendAI Interaction*. This stage utilizes the core HADF innovation where the AI acts as a "complementary reasoning partner".

C. *ExtendAI Interaction Sample: SMC-AI Dialogue*

- *SMC (Proposed Action Plan):* "I intend to dispatch the CPB directly to the LKP while the helicopter initiates an 'Expanding Square' search pattern centered on the last known coordinates. The commercial vessels will stand by 5 miles to the West.".
- *ExtendAI (Feedback & Reasoning Extension):* "The plan is appropriate for rapid deployment. However, *based on drift analysis (6B North wind), the PoC has shifted 3.2 miles South-Southeast from the LKP. Reasoning Gap Identified:* Utilizing an 'Expanding Square' with the helicopter may delay detection due to the high drift rate.
    - *Proposed Extension*: It is recommended to use a 'Creeping Line' search along the drift axis. Furthermore, repositioning the commercial vessels to form a 'Visual Barrier' to the South will increase the Probability of Detection (PoD) by 15%.".
- *Final Decision*: The SMC evaluates the feedback, accepts the PoC shift, and modifies the search pattern, maintaining ultimate authority over the execution.

Also, the next table shows the step-by-step interaction:

Table 2. Step-by-Step Interaction Table

Operational Stage	Human Action (SMC)	ExtendAI Contribution (GenAI/LLM)	Collaborative Outcome
Awareness	Receives LKP and weather data.	Automated data organization and cross-referencing.	Rapid situational awareness.
Initial Action	Designates OSC and initial assets.	Drift prediction and survival time estimation (Lagrange model).	Accurate determination of search area.

Planning	Formulates initial operational rationale.	Identifies cognitive gaps and provides highlighted feedback.	Optimized plan based on computational algorithms.
Integration	Evaluates AI recommendations.	Incorporates real-time sensor and asset data.	Increased decision confidence (76%).
Final Decision	Final approval and execution.	Continuous monitoring and suggestion of dynamic adjustments.	Reduced human error and faster recovery time.

Finally, the next figure shows the relatives operations of this scenario:

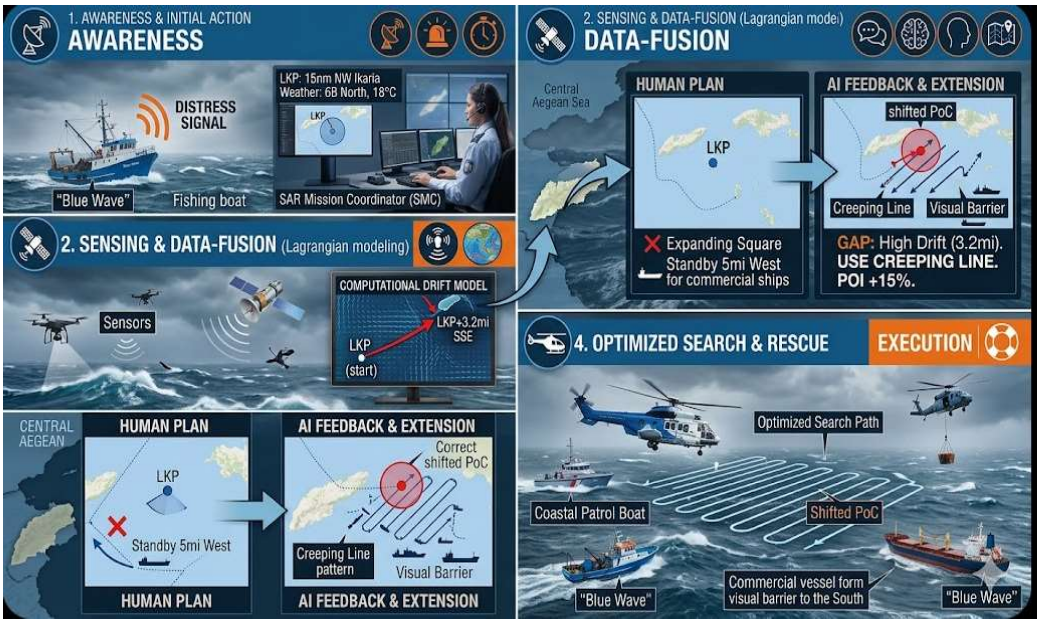

Figure 4. Scenario operation (by authors)

4.2 *Deployment consideration*

The successful implementation of the proposed framework requires a careful system architecture strategy, adapted to the specific telecommunication conditions of a maritime environment. In land-based infrastructures, with Search and Rescue Coordination Centers (MRCC), the use of Cloud-based LLMs is satisfactory, as the reliable broadband connection offers a utilization of models with enormous computing power. On the other hand, for operations performed on board (shipboard deployment) or in remote maritime zones, limited connectivity forces the choice of Edge AI solutions.

In low bandwidth (denied/degraded environments), the use of locally installed open-source models (e.g. Llama, Mistral or Phi-3) offers an advantage as there can be an implementation of LLM use, without the need for constant access to the internet. At the same time, the integration of modern satellite technologies such as VSAT and Iridium, or the use of hybrid connectivity models, are key factors for the future expansion of the system. In general, the choice of the appropriate architecture (Cloud vs Edge) depends on the operational context and the respective real-time response requirements.

5. Conclusions

AI offers substantial benefits in maritime safety and efficiency, acting as a complementary tool to human expertise. Continuous research and collaboration among stakeholders are essential to address these limitations and unlock the full potential of AI in maritime operations. The goal of using Gen AI is to complement and enhance the reasoning processes of the MSAR (Maritime Search and Rescue) user within an MRC (Maritime Rescue Coordination Centre), integrating AI more closely into the decision-making process. It aims to assist users in reflecting on and identifying potential gaps in their reasoning, leading to slightly better outcomes in the SAR (Search and Rescue) process.

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The Effects of Exogenous Shocks on the Baltic Dry Index

Doğanay Yıldırım [1]*, Sercan Erol [2]

[1] Samsun University, Türkiye

[2] Karadeniz Technical University, Türkiye

* Corresponding author: doganay.yildirim@samsun.edu.tr.

Abstract. This study examines the movements of the Baltic Dry Index (BDI) during periods of major exogenous shocks of different origins in the dry bulk shipping market. The research is framed within the context of the fragility of international supply chains, the sensitivity of freight markets to supply-demand imbalances, and the critical role of maritime transport in global trade. The study focuses on four major exogenous shocks that coincided with periods of significant volatility in freight market conditions: the COVID-19 pandemic, the grounding of the Ever Given in the Suez Canal, the Russia-Ukraine War, and attacks on commercial vessels in the Red Sea. The COVID-19 pandemic disrupted port operations, reduced vessel availability, slowed logistics processes, and increased volatility in freight rates. The Ever-Given incident caused a six-day blockage in the Suez Canal, disrupting global maritime traffic, extending delivery times, and increasing costs on certain routes. The Russia-Ukraine War has heightened uncertainty in global supply chains, particularly regarding grain and energy transportation, and has been associated with higher volatility in the freight market. Similarly, attacks on commercial vessels in the Red Sea have highlighted maritime security risks and led to route changes. These events provide a comparative framework for explaining how different exogenous shocks were reflected in dry bulk freight market conditions. The study evaluates BDI movements through graphical comparisons and descriptive statistics cantered around the selected shock dates. The findings are interpreted as evidence of the temporal relationship between exogenous shocks and BDI movements rather than definitive causal effects.

Key Words: Baltic Dry Index, Exogenous Shocks, COVID-19, Red Sea, Russia–Ukraine War

1. Introduction

Maritime transport is one of the cornerstones of global trade and plays a critical role in the functioning of the world economy. A large share of global trade by volume is carried by maritime transport, making it an indispensable component of international supply chains. According to UNCTAD, maritime transport accounts for more than 80% of global trade by volume, with the global volume of maritime trade reaching 12,720 million tons in 2024 (UNCTAD, 2025).

Freight rates in maritime transport are determined by a highly dynamic market structure shaped by the interplay of supply and demand. Fleet capacity, vessel supply, fuel costs, commodity demand, industrial production, and macroeconomic developments are among the key factors that decisively shape the freight market (Stopford, 2009; Notteboom & Vernimmen, 2009; Gu & Liu, 2022). One of the most widely used indicators for tracking these changes in the dry bulk shipping market is the Baltic Dry Index. The Baltic Dry Index is recognised as a key indicator for both maritime markets and global trade activities because it reflects spot freight conditions in the dry bulk shipping sector (Lin & Sim, 2013; Lin et al., 2019; Bai et al., 2021; Bandyopadhyay & Rajib, 2023). However, in recent years, maritime transport markets have been confronted not only with traditional supply-and-demand dynamics but also with exogenous shocks emerging on a global scale. The COVID-19 pandemic, the Russia-Ukraine War, the grounding of the Ever Given in the Suez Canal, and attacks on commercial vessels in the Red Sea have demonstrated that maritime transport networks are vulnerable to various types of disruptions. These developments have become closely linked to freight market conditions through numerous operational and economic factors, including port operations, route safety, vessel accessibility, insurance costs, fuel consumption, and delivery times (Cui et al., 2023; Sun et al., 2024; UNCTAD, 2024b).

In this context, the Baltic Dry Index provides a useful indicator of how freight markets respond during periods of global economic slowdown, geopolitical uncertainty, and security-related disruptions. However, rather than establishing a direct and definitive causal relationship between external shocks and BDI movements, evaluating such market movements by examining how these developments coincided with with freight market fluctuations during the same periods provides a more cautious approach. Therefore, rather than measuring the precise causal effects of the selected external shocks on the BDI, this study evaluates how BDI movements changed during these periods within a descriptive and comparative framework. This study examines movements in the Baltic Dry Index during major exogenous shocks of different origins in the 2019 to 2025 period, thereby describing how the dry bulk freight market responded under different shock conditions. In this context, the study examines the COVID-19 pandemic, the six-day blockage of the Suez Canal caused by the Ever Given, the Russia-Ukraine War, and attacks on commercial vessels in the Red Sea. The study evaluates BDI movements through graphical comparisons and descriptive statistics; it interprets the findings not as definitive causal conclusions, but as descriptive evidence of the temporal relationship between periods of exogenous shocks and freight market conditions.

2. Literature Review

Freight rates in maritime transport are among the market indicators that exhibit high volatility due to their sensitivity to changes in supply-demand conditions, operational costs, and global economic developments (Lim et al., 2019). One of the indicators widely used to track these changes in the dry bulk shipping market is the Baltic Dry Index. The Baltic Dry Index is recognised as a key indicator, particularly for reflecting market conditions related to major dry bulk cargo shipments (Stopford, 2009). During periods of economic growth, increased demand for raw materials can boost cargo volumes, creating upward pressure on BDI levels. Conversely, during periods of economic slowdown, a decline in demand for raw materials weakens global trade volumes and can create downward pressure on dry bulk freight rates (Papailias et al., 2017; Lin et al., 2019).

Recent studies indicate that the maritime transport sector has become increasingly vulnerable to exogenous shocks such as the pandemic, geopolitical conflicts, trade restrictions, and security-related disruptions in strategic sea lanes (Rothengatter, 2011; UNCTAD, 2023). Such developments are associated with fluctuations in freight markets, driven by route changes, longer voyage durations, increased fuel consumption, operational uncertainties, and changes in vessel availability (Dagestani, 2022; Cong et al., 2024). Xu et al. (2022) examined the relationship between new case counts and BDI volatility during the COVID-19 pandemic using a GARCH-MIDAS model with data from 2020 to 2022. The study's findings indicate that case counts remain significantly associated with BDI volatility even after controlling for other freight and operational variables. Similarly, Chang et al. (2023), in their study covering the 2019 to 2021 period, compared pre- and post-pandemic periods; they found that the factors determining the BDI changed after the pandemic, with port calls, iron ore and scrap steel prices, and confirmed COVID-19 case counts becoming more decisive.

The literature also highlights the importance of route disruptions and geopolitical risks for maritime freight markets. Tran et al. (2025) demonstrate that the blockage caused by the Ever Given vessel in the Suez Canal in 2021 was associated with high economic and environmental costs for maritime transport, including route deviations and delays, and increased the fragility of supply chains. According to UNCTAD, the Russia-Ukraine War has impacted maritime trade logistics by disrupting cargo flows, particularly those originating in Europe, and by causing fluctuations in freight markets (UNCTAD, 2022). Erol (2024) examined the early-stage impacts of the Russia-Ukraine War on maritime trade and transportation in the Black Sea, noting that during the conflict, vessel operating and logistics costs increased, congestion and supply chain disruptions emerged in major logistics corridors, and alternative trade routes gained greater importance.

Monge et al. (2023), who examined the relationship between geopolitical risks and freight markets, analysed the behaviour of the Baltic Dry Index and West Texas Intermediate oil prices using monthly data from 1985 to 2021. The study's findings indicate that following geopolitical shocks, BDI returns tend to revert to their long-term trend, whereas oil prices exhibit more persistent responses. Furthermore, structural break and wavelet analyses reveal that geopolitical risks are associated with significant breaks in both freight rates and oil prices. More recently, UNCTAD (2024a) noted that security-related disruptions in the Red Sea have increased global maritime transport costs and exerted upward pressure on freight markets.

3. Materials and Methods

This study uses the Baltic Dry Index (BDI) as a key indicator to assess changes observed in the dry bulk freight market during periods of exogenous shocks. The BDI was selected as the empirical indicator for this study because it reflects freight conditions in the dry bulk shipping market. The research is based on BDI data from 2019 to 2025. This period provides a suitable timeframe for analysis, as it encompasses a time span during which global maritime transport markets faced exogenous shocks of different origins.

The study examines four major exogenous shocks: the COVID-19 pandemic, the six-day blockage in the Suez Canal caused by the Ever Given, the Russia-Ukraine War, and attacks on commercial vessels in the Red Sea. These events were included in the comparative analysis because they occurred during the same time period in which significant fluctuations were observed in the dry bulk freight market. Thus, the study examined how external developments of different natures coincided with movements in the BDI.

Methodologically, the study is based on a descriptive and comparative research design rather than a causal econometric modelling approach. Therefore, the findings are interpreted not as definitive causal effects of exogenous shocks on the BDI, but rather as descriptive evidence of the temporal relationship between the selected shock periods and BDI movements. This approach aims to reveal how changes in the BDI are shaped around the dates of the shocks; however, it does not make a definitive claim of causality that these changes stem solely from these events.

The movements of the Baltic Dry Index (BDI) from 2019 to 2025 were visualised using annual and overall period charts. Selected shock periods were marked on the time series charts, and changes in index values were evaluated by considering pre- and post-shock trends. Additionally, the direction and magnitude of fluctuations in the freight market were presented in a comparative manner using descriptive statistics, annual averages, and time-series comparisons. In this context, the analysis focuses on describing how the BDI responded during different periods of exogenous shocks and explaining the relationship between these movements and freight market conditions.

4. Results

Time series charts show that the Baltic Dry Index experienced significant fluctuations during the 2019–2025 period and that these fluctuations closely coincided with periods of exogenous shocks of different origins. The findings present the movements observed in the dry bulk freight market during these periods within a descriptive framework, rather than measuring the precise causal effects of the selected shocks on the BDI. As shown in Figure 1**,** the Baltic Dry Index remained at low levels during the first months of 2020. This period coincided with the COVID-19 pandemic, which reduced global trade volumes, disrupted port operations, and created uncertainty in logistics processes. In the early stages of the pandemic, the index fell to 461 points amid a contraction in global demand and a slowdown in shipping activities. However, starting in the middle of the year, a rapid recovery in BDI values was observed due to supply chain imbalances, limited shipping capacity, and, particularly, the resurgence of economic activity in China. Nevertheless, the index remained volatile for the remainder of the year and generally remained below pre-pandemic levels. This pattern indicates that BDI movements during the

COVID-19 period were linked to both the contraction in demand and the subsequent supply chain pressures.

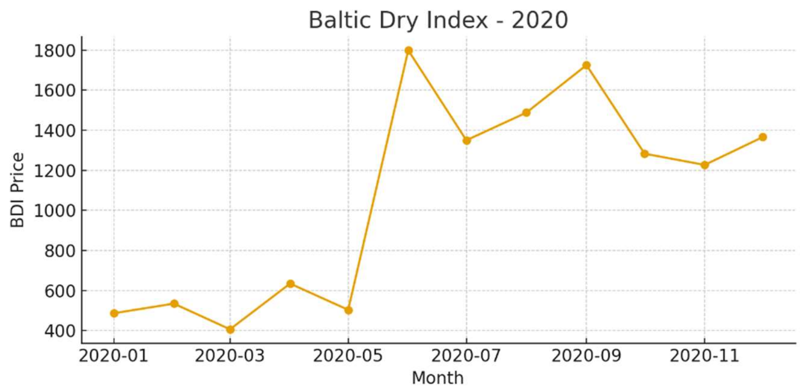

Figure 1. Baltic Dry Index – 2020

As shown in Figure 2**,** the Baltic Dry Index rose sharply in 2021. The six-day blockage caused by the Ever Given vessel in the Suez Canal led to disruptions in global maritime traffic, longer delivery times, and cost pressures on certain routes. This period coincided with the post-pandemic recovery in global trade, the persistence of logistics bottlenecks, and limited vessel supply. Under these conditions, the BDI rose above 2,000 points and reached very high levels in the third quarter of the year. Although a downward trend was observed in the index during the final months of the year, the fact that BDI values remained high throughout 2021 indicates that supply chain bottlenecks and capacity constraints were strongly reflected in freight market conditions.

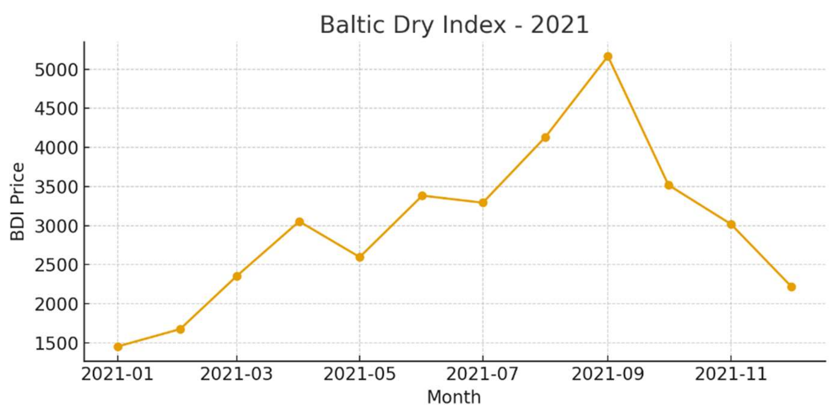

Figure 2. Baltic Dry Index – 2021

As shown in Figure 3, BDI values in 2022 followed a volatile trend during the same period marked by rising geopolitical uncertainty following the outbreak of the Russia-Ukraine War, route security issues, and risks related specifically to grain and energy transportation. The index remained at relatively high levels in the first month of the year, but a clear downward trend emerged starting in the middle of the year, driven by a slowdown in global demand and shifts in market expectations. Sharp declines were observed in the second half of the year, followed by a limited recovery in subsequent months. This trend suggests that during the war, the BDI was sensitive not only to geopolitical developments but also to global demand conditions and market expectations.

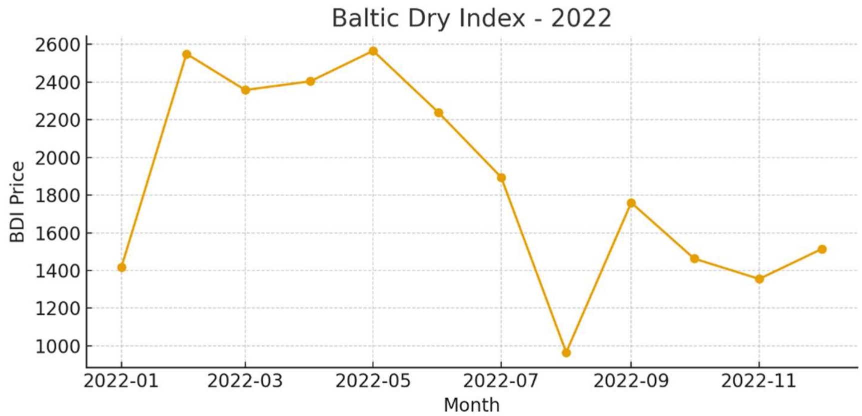

Figure 3. Baltic Dry Index – 2022

As shown in Figure 4**,** BDI values remained relatively low and flat during the first half of 2023. Increasing security risks in the Red Sea region and concerns about route safety led some vessels to opt for alternative routes, resulting in longer voyage durations and higher fuel costs. However, weak global demand during the same period limited the rise in freight rates to the expected extent. This situation suggests that cost increases alone are insufficient to drive up freight rates and that demand conditions play a significant role in BDI movements. In the second half of the year, the index rose amid uncertainties about global trade flows and geopolitical risks, with more pronounced increases in the final quarter. Although a limited decline was observed in the final month of the year, the index exhibited an upward trend heading into the end of 2023.

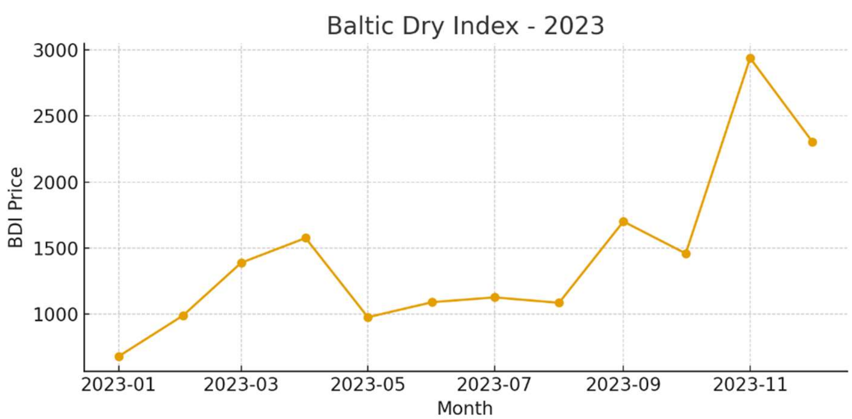

Figure 4. Baltic Dry Index – 2023

As shown in Figure 5, the Baltic Dry Index was volatile throughout 2024. While index values saw limited fluctuations in the first half of the year, a more pronounced rise emerged, particularly in the third quarter. In contrast, the fourth quarter saw a renewed downward trend in the freight market, and index values declined toward the end of the year. This period should be evaluated alongside changes in global trade volumes, fluctuations in dry bulk cargo demand, and uncertainties regarding maritime shipping routes, particularly security risks in the Red Sea. Consequently, 2024 suggests that the BDI followed a trajectory sensitive to both demand conditions and route security and geopolitical uncertainties.

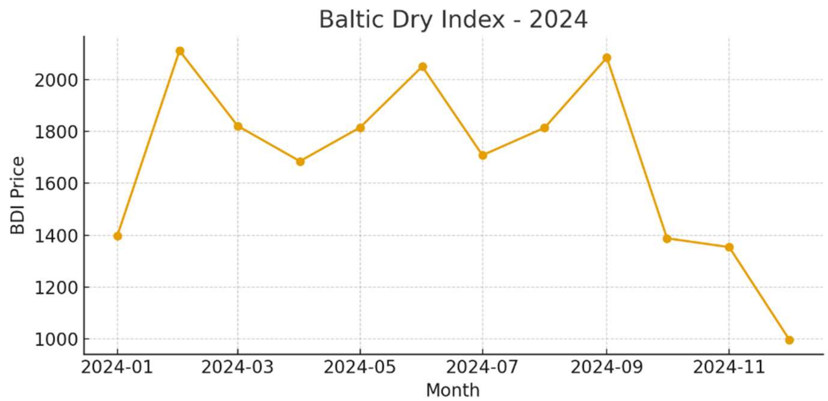

Figure 5. Baltic Dry Index – 2024

As shown in Figure 6**,** the Baltic Dry Index generally rose in 2025. The index, which was at relatively low levels in the first months of the year, rose gradually from the middle of the year onward and showed a more pronounced increase in the final quarter. This trend indicates a period in which demand conditions and cost pressures in the global dry bulk shipping market have regained strength. However, this increase should be evaluated in the context of broader market conditions, demand developments, and freight market expectations, rather than attributed solely to a single exogenous shock.

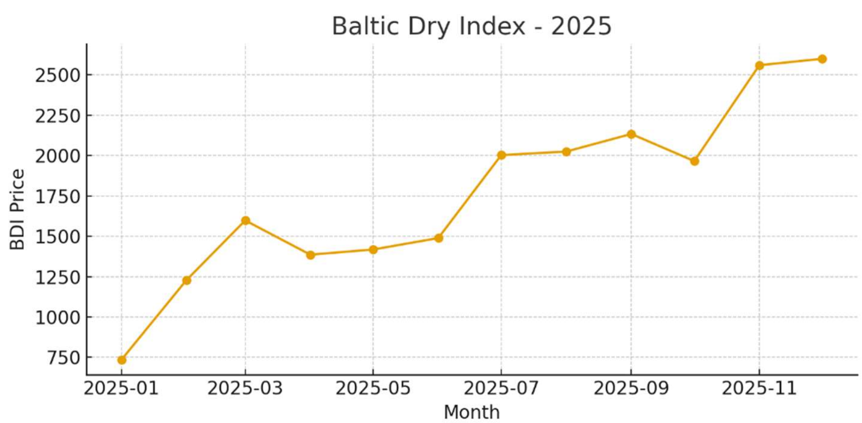

Figure 6. Baltic Dry Index – 2025

As shown in Figure 7, the overall BDI trend for the 2019 to 2025 period indicates that the dry bulk freight market is highly sensitive to global economic and geopolitical developments. In 2020, a significant decline in index values was observed during the COVID-19 pandemic, while in 2021, BDI values rose rapidly amid supply chain disruptions, post-pandemic recovery, and logistical bottlenecks. In 2022, market volatility increased with the outbreak of the Russia-Ukraine War, and the index entered a downward trend in the latter part of the year. In 2023 and 2024, the market followed a volatile yet relatively more balanced trajectory; security risks in the Red Sea region and uncertainties in global trade flows were assessed alongside periodic increases. In 2025, a gradual recovery trend in BDI values was observed. Overall, the findings indicate that the BDI exhibits significant fluctuations during periods marked by global crises, geopolitical uncertainties, route safety issues, and changes in demand conditions. However, these results should be interpreted not as definitive evidence of the causal effects of exogenous shocks on the BDI, but rather as descriptive evidence of the temporal relationship between the selected shock periods and movements in the dry bulk freight market.

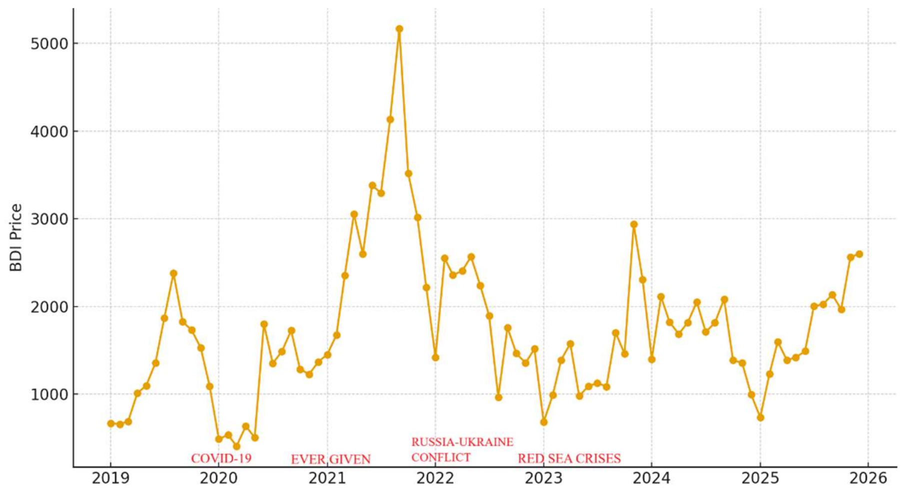

Figure 7. Baltic Dry Index 2019–2025 Period

5. Conclusion

This study examines how the dry bulk freight market behaves during periods of various types of global exogenous shocks, using Baltic Dry Index data for the 2019 to 2025 period. The findings indicate that the BDI exhibited significant fluctuations during these periods and that the dry bulk freight market is structurally sensitive to external developments. However, these findings should be interpreted not as definitive causal effects of exogenous shocks on the BDI but rather as descriptive evidence revealing the temporal relationship between the selected shock periods and BDI movements.

The four exogenous shocks examined in the study are linked to freight market conditions through various channels. During the early stages of the COVID-19 pandemic, the contraction in global demand, disruptions in port operations, and uncertainties in logistics processes coincided with the downward trend in the BDI. Following the pandemic, supply chain bottlenecks, constraints on transport capacity, and the recovery process in global trade were observed alongside an upward trend in the BDI. This indicates that BDI movements during the pandemic period must be evaluated in conjunction with both the contraction in demand and the subsequent supply and capacity pressures that emerged.

The six-day blockage caused by the Ever Given in the Suez Canal has emerged as a significant external event that led to disruptions in global maritime traffic, longer delivery times, and cost pressures on certain routes. However, the reflection of this event in the BDI should be assessed not only in light of the canal blockage but also in conjunction with market conditions such as the post-pandemic recovery in global trade, logistics bottlenecks, and limited vessel supply. Consequently, the high BDI levels observed in 2021 present a picture that can be explained by the convergence of multiple market factors during that period.

The Russia-Ukraine War is viewed as a significant geopolitical development that has created uncertainty in the freight market, particularly regarding grain and energy transportation, route security, insurance costs, and regional trade flows. The findings indicate that volatility in the BDI increased when the war began; however, the index subsequently moved in a manner sensitive to changes in global demand conditions and market expectations. This suggests that freight market responses to geopolitical shocks are not one-sided but are shaped by demand, supply, route security, and the overall economic outlook.

Attacks on commercial vessels in the Red Sea and rising security risks have created a significant area of risk for maritime transport markets, leading to route changes, longer voyage durations, and pressure for higher fuel costs. However, the findings indicate that the extent to which these cost pressures are reflected in freight rates can vary depending on global demand conditions. In particular, the limited reflection of cost increases in the BDI during periods of weak demand highlights the decisive role of demand conditions in freight markets.

Overall, the study indicates that the BDI is a key indicator that reflects not only global economic activity but also developments related to supply chain disruptions, geopolitical uncertainties, route security issues, and market expectations. However, it is incorrect to attribute BDI movements to a single factor. Freight markets are shaped by the simultaneous interaction of numerous factors, including supply-demand balance, fleet capacity, fuel costs, route security, commodity demand, and the macroeconomic outlook. Therefore, movements observed in the BDI during periods of exogenous shocks should be evaluated within the broader context of market conditions.

From a practical perspective, the findings underscore the importance of maritime sector stakeholders closely monitoring freight market indicators during periods of exogenous shocks. For shipowners, charterers, cargo owners, logistics companies, and policymakers, evaluating BDI movements in conjunction with indicators such as route safety, port congestion, fuel costs, commodity demand, and geopolitical risks can contribute to more sound decision-making processes. Especially during periods of uncertainty, flexible route planning, evaluating alternative trade corridors, utilizing freight risk management tools, and strengthening early warning systems can enhance the sector’s resilience to shocks.

The main limitation of this study is that it relies on a descriptive and comparative approach rather than a causal econometric model. Therefore, the results highlight the temporal relationship between shock periods and BDI movements rather than measuring the exact magnitude or persistence of shock-related changes in the BDI. Future studies could examine the magnitude, duration, and persistence of exogenous shocks on freight markets in greater detail using econometric methods such as

VAR, VECM, ARDL, or event studies. Furthermore, analyzing BDI data in conjunction with AIS-based vessel movements, port congestion indicators, commodity trade data, and geopolitical risk indices could contribute to a more comprehensive explanation of how exogenous shocks manifest in maritime transport markets.

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Future Maritime Workforce in the Green and Digital Era

Capt. (Dr.) Yogesh Chandralal Shah*[1]

[1]Indian Maritime University – Navi Mumbai Campus, India

* Corresponding author: ycshah@imu.ac.in;

Abstract. The maritime sector is undergoing an unprecedented phase of transformation driven by three converging forces: decarbonisation, digitalisation, and heightened geopolitical risk. These transitions are reshaping not only ship technologies and regulatory frameworks but also the skills, safety exposure, and welfare needs of the global maritime workforce. Stricter emissions controls, the introduction of alternative fuels, expanding digital and automated systems, and recurring security disruptions collectively demand new operational competencies and greater organisational resilience from seafarers and shore-based personnel alike. This study examines how these structural shifts alter workforce requirements, with particular attention to labour-supplying countries in the Global South. Using a comparative policy and institutional analysis of international regulations, industry practices, and national training systems, the paper synthesises evidence on alternative-fuel readiness, digital and cyber competence, and emerging psychosocial pressures. A focused comparison of India, the Philippines, and China highlights differences in scale, governance models, and transition preparedness. The findings identify critical capability gaps in fuel-specific safety training, simulator infrastructure, quality assurance in maritime education, and ethical recruitment practices. The paper argues that workforce readiness constitutes the enabling condition for safe, equitable, and effective maritime transition. It concludes that India, given its institutional base and policy momentum, can move beyond labour supply to become a regional leader in maritime skills, safety, and sustainable development through targeted reforms and coordinated investment.

Key Words: maritime workforce; decarbonisation; digitalisation; just transition; India.

1. Introduction: A Transition Like No Other

Maritime transport has long been the backbone of global trade, carrying between 80 and 90 per cent of goods by volume (UNCTAD, 2024). Throughout history, the sector has adapted to successive technological shifts — from sail to steam, coal to oil, and paper charts to electronic navigation. Each transition altered ship design, reshaped operational practices, and redefined the skills expected of seafarers. However, the present moment differs from earlier phases of change in both its scale and urgency.

The first driver of this transformation is decarbonisation. The International Maritime Organization's Revised GHG Strategy (2023) sets an ambition to achieve net-zero emissions from international shipping "by or around 2050," with interim checkpoints targeting reductions in carbon intensity of 40 per cent by 2030 and 70 per cent by 2040 (IMO, 2023). In parallel, the European Union has extended its Emissions Trading System (EU ETS) to shipping, requiring companies to purchase allowances for a growing share of their emissions — 40 per cent in 2024, 70 per cent in 2025, and full coverage from 2026 (European Commission, 2024). The FuelEU Maritime Regulation further imposes limits on the greenhouse-gas intensity of energy used on board vessels trading in the EU/EEA. These measures are not merely regulatory adjustments; they influence voyage economics, fuel choices, reporting systems, and day-to-day shipboard operations.

A second driver is digitalisation and automation. Ships are increasingly embedded within global data networks through sensors, satellite connectivity, and performance-monitoring software. Concepts such as Maritime Autonomous Surface Ships (MASS) are moving steadily towards regulatory recognition, with the IMO expected to finalise a non-mandatory MASS Code by 2026 (IMO, 2024). As a result, the role of the seafarer is evolving. Modern crews are required not only to manage equipment but also to interpret data, oversee automated systems, and maintain cyber security.

A third driver arises from geopolitics and security. Maritime transport remains directly exposed to global conflict and instability. Attacks on merchant vessels in the Red Sea during 2023–2024 forced widespread rerouting and demonstrated the physical and psychological risks faced by seafarers. Similarly, disruptions linked to the war in Ukraine have affected trade flows and increased operational uncertainty in the Black Sea region (UNCTAD, 2024). These developments underline that seafarers experience the immediate consequences of geopolitical shocks.

What distinguishes the current phase of change is the convergence of these forces. Decarbonisation, digitalisation, and security pressures are unfolding simultaneously rather than sequentially, compressing the time available for adaptation. Moreover, they interact with one another: alternative fuels require digital monitoring and specialised safety protocols; carbon pricing influences routing and cost structures; and automation reshapes onboard responsibilities. Together, these trends intensify both operational complexity and risk exposure.

Against this backdrop, the maritime workforce emerges as the central enabling factor of transition. Policies, technologies, and market instruments can only succeed when the people operating ships possess the necessary skills, training, and institutional support. The challenge is therefore not solely technical but also social and ethical: who bears the costs of transition, and how can benefits be distributed more equitably across ship-owning and seafarer-supplying nations?

This paper addresses these questions through a structured analysis. Section 2 examines the implications of decarbonisation, digitalisation, and geopolitics for workforce skills and safety. Section 3 explores global labour market dynamics and the concept of a just transition. Section 4 focuses on India's position within this evolving landscape. Section 5 presents illustrative case examples of institutional and industry responses. Section 6 outlines policy and institutional pathways, and Section 7 concludes by reaffirming that workforce readiness is central to a safe and equitable maritime future.

2. Global Transitions and Workforce Implications

2.1 Decarbonisation and Emerging Competencies

Decarbonisation represents the most far-reaching structural change currently confronting international shipping. The IMO's Revised Greenhouse Gas Strategy (2023) sets a pathway towards net-zero emissions from international shipping by or around 2050, supported by interim reduction checkpoints for 2030 and 2040 (IMO, 2023). Regional mechanisms, particularly the European Union's Emissions Trading System (EU ETS) and the FuelEU Maritime Regulation, have already translated these ambitions into enforceable operational requirements. Under the EU ETS, operators must monitor, report and surrender allowances for an increasing share of emissions, reaching full compliance by 2026 (European Commission, 2024). FuelEU Maritime, applicable from January 2025, mandates progressive reductions in the well-to-wake greenhouse-gas intensity of marine fuels, linking fuel choice directly to voyage economics and compliance costs (EMSA, 2025).

For seafarers, these developments convert climate policy into everyday operational reality. Alternative fuels such as liquefied natural gas (LNG), methanol, ammonia and hydrogen each introduce distinct safety and handling challenges. LNG involves cryogenic risks; methanol burns with an almost invisible flame; ammonia presents acute toxicity hazards; and hydrogen is susceptible to leakage and embrittlement. Consequently, crews require not only conventional engineering competence but also fuel-specific safety knowledge, chemical awareness and advanced emergency response capabilities (Lloyd's Register, 2025).

The scale of retraining implied by this transition is considerable. Estimates suggest that hundreds of thous ands of seafarers will require additional training within the coming decade to safely manage alternative fuels (Reuters, 2024). Without timely upskilling, the sector risks safety incidents, environmental liabilities and operational disruption. Moreover, the competence demands extend beyond ships. Shore-based personnel — ship managers, charterers, compliance officers, surveyors and port authorities — must interpret carbon indicators, trading obligations and overlapping regulatory regimes. Decarbonisation therefore generates a cascading skills agenda across the entire maritime ecosystem.

2.2 Digitalisation, Automation and the Changing Nature of Work

Alongside decarbonisation, shipping is undergoing rapid digital transformation. Vessel-performance optimisation tools, predictive maintenance systems, digital twins and remote inspection technologies are increasingly embedded in everyday operations. The widespread acceptance of remote surveys and electronic certification since the pandemic has accelerated this shift towards digitally enabled compliance (DNV, 2022).

These developments substantially reshape competence expectations. Traditional seamanship and engineering skills must now be complemented by data literacy and cyber awareness. Officers are expected to interpret algorithmic outputs, supervise automated processes and safeguard onboard information systems. Recognising these risks, the IMO has required cyber-risk management to be incorporated within Safety Management Systems since 2021 (IMO, 2021).

Automation extends this trajectory further. Maritime Autonomous Surface Ships (MASS) are progressing from experimental projects towards structured regulation, with a non-mandatory MASS Code anticipated by 2026 (IMO, 2024). Several administrations are already piloting semi-autonomous operations. While full autonomy for deep-sea shipping remains distant, short-sea and coastal applications are advancing steadily.

Rather than eliminating jobs, automation is likely to reconfigure them. Emerging roles include remote operators, system supervisors and cyber-incident responders. Evidence from the SkillSea initiative indicates that futureproof skills combine technical competence with transversal capabilities such as communication, problem-solving and systems thinking (SkillSea, 2023). In effect, tomorrow's officer functions less as a manual operator and more as a systems integrator managing complex human–machine interactions.

2.3 Geopolitical Disruptions and Security Risks

Maritime labour is equally affected by geopolitical instability. Attacks on merchant vessels in the Red Sea during 2023–2024 forced widespread rerouting and increased voyage times and costs (UNCTAD, 2024). Similar disruptions in the Black Sea following the Russia–Ukraine conflict have constrained trade flows and heightened operational uncertainty. For crews, these events translate directly into longer contracts, increased stress and elevated exposure to physical risk.

The psychological dimension of such disruptions is increasingly recognised. Isolation, uncertainty regarding repatriation and the threat of violence impose significant welfare pressures. Amendments to the Maritime Labour Convention adopted by the International Labour Organization strengthen provisions related to shore leave, repatriation and protection from harassment and violence (ILO, 2025). However, effective implementation by flag states and employers remains critical to translating these protections into practice.

Geopolitical risk also intersects with technological change. Rerouting raises fuel consumption and therefore carbon costs under emissions regimes. At the same time, digital dependence introduces new vulnerabilities to cyberattack. Workforce preparedness must therefore encompass not only technical competence but also resilience, adaptability and access to psychosocial support.

2.4 Intersections and Cumulative Impacts

The defining feature of the current period is the convergence of these transitions. Decarbonisation, digitalisation and security pressures operate simultaneously and reinforce one another. Alternative fuels rely on digital monitoring and control systems; conflict-driven rerouting increases both fuel use and emissions costs; and automation reshapes responsibilities while increasing cognitive load.

The cumulative effect is a marked escalation in the professional, technical and emotional demands placed on seafarers. With adequate training, institutional support and welfare safeguards, these transitions can strengthen the profession and enhance safety outcomes. If neglected, they risk deepening skill shortages, undermining operational reliability and weakening the human foundation upon which global maritime trade ultimately depends.

3. Labour Market Dynamics and the Just Transition

3.1 Officer Shortages and Structural Imbalances

Even prior to the current green and digital transitions, the maritime industry struggled to align labour supply with demand. The BIMCO/ICS Seafarer Workforce Report identified a global shortage of more than twenty-six thousand officers and warned that the gap could widen if training pipelines did not expand in step with fleet growth (BIMCO & ICS, 2021). While the availability of ratings was broadly balanced, demand for certified officers — particularly electro-technical officers and other specialised roles — remained consistently higher than supply.

These shortages are reinforced by demographic and institutional pressures. Ageing officer cohorts in several developed maritime nations reduce replacement rates, while younger entrants often view seafaring as less attractive due to extended contracts, family separation and limited shore-side mobility. Attrition also occurs within training systems: many cadets struggle to secure mandatory sea time, delaying or preventing certification. Wage competition from shore-based industries and persistent welfare concerns further weaken retention.

The result is a labour market characterised not only by quantitative deficits but also by qualitative mismatches. As competencies related to alternative fuels, digital systems and cyber resilience become essential, existing gaps risk deepening. Without timely intervention, such shortages may compromise operational safety and constrain the industry's ability to meet decarbonisation and compliance targets.

3.2 Supply-Country Dynamics: India, the Philippines and China

Global seafaring labour is concentrated in a small number of supply countries. The Philippines remains the largest contributor, accounting for roughly one-quarter of the world's seafarers (POEA, 2023). India is among the next largest suppliers, and China is likewise recognised as a major contributor to the global workforce (DG Shipping, 2024; UNCTAD, 2024). These nations exhibit distinct institutional models and transition capacities.

India maintains a sizeable pool of English-speaking officers supported by national institutions such as the Indian Maritime University and the Directorate General of Shipping. Estimates place the number of active Indian seafarers between 2.5 and 4.8 lakh, depending on definitional coverage (DG Shipping, 2024). While recent policy initiatives emphasise skilling and training expansion, challenges remain, including uneven quality among private training institutes, limited readiness for alternative fuels and vulnerability to unethical recruitment practices.

The Philippines benefits from a highly centralised governance structure under the Philippine Overseas Employment Administration, which coordinates training, certification and international deployment. This system has enabled consistent global placement and strong market visibility. However, oversupply of ratings and downward wage pressure create long-term sustainability concerns.

China has invested heavily in state-led academies and fleet-linked training systems, particularly in high-value segments such as LNG carriers and offshore operations. Although Chinese officers are increasingly visible in international markets, language barriers and issues of certification recognition continue to affect deployment flexibility.

These contrasts are summarised in Table 1, which compares scale, institutional strengths and structural challenges across the three principal supply nations.

Table 1. Comparative Overview of Seafarer Supply Nations (2023–2024)

Indicator	India	Philippines	China
Estimated active seafarers	2.5 - 4.8 lakh	~5.5 - 6 lakh	~3 - 4 lakh
Share of global workforce	~10 - 12%	~25%	~12 - 14%
Institutional strength	IMU, DG Shipping, mixed private METs	Centralised training and deployment under POEA	State academies, fleet-linked training
Key strengths	English-speaking officers, academic base	Global reputation, coordinated deployment	LNG/offshore expertise
Key challenges	Uneven quality, limited alternative-fuel training, recruitment malpractice	Oversupply of ratings, wage pressure	Language and certification barriers

Source: Compiled from DG Shipping (2024), POEA (2023), UNCTAD (2024), and author's synthesis.

3.3 The Just Transition Lens

Debates on workforce change increasingly draw upon the concept of a just transition, which emphasises that workers should not disproportionately bear the social and economic costs of environmental and technological transformation (ILO, 2022). Applied to the maritime sector, this perspective extends beyond technical upskilling to questions of fairness, protection and participation.

First, access to affordable training and reskilling opportunities is essential. Without targeted support for alternative-fuel handling and digital competencies, seafarers from developing economies risk exclusion from higher-value roles. Second, the transition must guard against precarity. Labour shortages, extended contracts, fraudulent recruitment and abandonment during financial distress highlight the continued importance of effective Maritime Labour Convention enforcement. Third, workers and their representative bodies require meaningful participation in policy discussions.

Decisions on standards, certification and safety protocols directly shape working lives and therefore benefit from practitioner input.

Viewed through this lens, workforce transition is not merely a problem of closing skills gaps but a broader socio-economic challenge concerning equity between ship-owning and labour-supplying nations.

3.4 Interlinkages with Global Value Chains

Seafarers constitute a critical yet often invisible component of global value chains. Their labour enables the continuous movement of containers, energy commodities and bulk cargoes that underpin international trade. Nevertheless, the costs and risks generated by regulatory and market shifts are frequently transmitted downstream to crews. Carbon pricing mechanisms may indirectly lengthen voyages or intensify monitoring demands, while digitalisation initiatives designed for efficiency often add new responsibilities without proportional institutional support.

Recognising these interdependencies is therefore essential. Workforce planning cannot be isolated from trade policy, energy markets or security considerations. A holistic approach situates seafarers within broader debates on supply-chain resilience and climate justice, ensuring that human capabilities remain central to the sustainability of maritime transport.

4. India's Maritime Workforce in Transition

4.1 National Context and Policy Framework

India has consolidated its position as one of the world's leading suppliers of seafarers, alongside the Philippines and China. Official statistics from the Directorate General of Shipping indicate more than 2.5 lakh active Indian seafarers, while broader estimates suggest totals approaching 4.8 lakh depending on definitional coverage (DG Shipping, 2024. Although precise figures vary, the overall trend is unequivocal: India constitutes a major and expanding labour pool for the global fleet.

National policy direction reflects this strategic importance. Maritime India Vision 2030 identifies workforce development and skilling as central pillars of competitiveness, recognising that maritime human capital underpins both employment generation and industrial growth (NITI Aayog, 2021). Recent investments in specialised training infrastructure — including facilities such as the Indian Ship Technology Centre at Visakhapatnam and new regional centres of excellence — signal an intent to embed advanced competencies within domestic institutions rather than relying solely on external demand (Press Information Bureau, 2025a; 2025b).

Complementing these initiatives, the Government of India has announced substantial maritime modernisation outlays aimed at upgrading ports, shipbuilding capacity and skill development programmes (Press Information Bureau, 2025c). This broader industrial push creates an opportunity to integrate seafarer training with national logistics and manufacturing strategies, moving beyond a narrow labour-export model towards higher-value participation in the maritime economy.

4.2 Institutional Strengths

India's training ecosystem possesses a comparatively strong institutional foundation. The Indian Maritime University provides degree-level education, research capability and curriculum standardisation across multiple campuses, while the Directorate General of Shipping regulates certification, licensing and compliance. In parallel, a large network of private Maritime Education and Training institutes contributes scale and geographic reach. Together, these actors create a diversified system capable of producing officers and ratings across a wide spectrum of vessel types.

Language proficiency in English has historically provided Indian officers with an advantage in international placements, facilitating communication on multinational ships and with global operators. Indian seafarers are often regarded as technically competent, adaptable and disciplined, attributes that have supported their presence in tanker, bulk carrier and cruise segments (Ghosh, 2022). These characteristics constitute an important platform for future upgrading.

4.3 Persistent Gaps and Challenges

Despite these strengths, several structural constraints continue to limit India's readiness for emerging transitions.

First, training quality remains uneven. While IMU campuses and established academies maintain high standards, many smaller private institutes face constraints related to infrastructure, faculty expertise and sea-time placement opportunities. Such disparities create bottlenecks in officer certification and affect overall system credibility.

Second, readiness for alternative fuels is limited. Dedicated simulators, safety laboratories and specialised curricula for methanol, ammonia or hydrogen operations remain scarce. Without accelerated investment, India risks lagging behind supply countries that are already integrating alternative-fuel modules into mainstream training.

Third, recruitment malpractice and abandonment persist as reputational risks. Unauthorised intermediaries occasionally charge illegal fees or place seafarers with substandard employers, while cases of unpaid wages or delayed repatriation undermine welfare protections. Strengthened enforcement of the Registered Recruitment and Placement Service Licence system and closer monitoring of employers are therefore essential (ISWAN, 2024).

Finally, welfare and mental-health pressures have become more visible. Prolonged contracts, exposure to security risks and limited shore leave contribute to stress and fatigue. Although recent amendments to the Maritime Labour Convention strengthen safeguards, consistent implementation at the national level remains uneven.

4.4 Comparative Insights

Comparison with other leading supply nations highlights both opportunities and vulnerabilities for India.

The Philippines has institutionalised a centralised deployment framework through the Philippine Overseas Employment Administration, enabling coordinated training, certification and placement. This approach enhances predictability and market visibility, whereas India's decentralised structure, while flexible, can expose seafarers to inconsistent standards.

China, by contrast, closely aligns maritime training with national industrial policy, particularly in high-value sectors such as LNG carriers, offshore energy and technologically advanced vessels. If India remains concentrated in conventional segments, it risks losing competitiveness in emerging niches that command higher wages and strategic value.

India's comparative advantage therefore lies in its scale, language capability and institutional base. Sustaining these strengths requires deliberate upgrading rather than reliance on historical momentum.

4.5 India's Opportunity for Strategic Leadership

India's future role need not be confined to labour supply alone. With targeted reforms, it can position itself as a regional leader in skills and safety for the Global South. Three strategic shifts are particularly relevant.

First, the focus must move from volume to value by prioritising advanced competencies such as alternative-fuel operations, LNG and offshore systems, cyber security and integrated ship management. Second, training policy should become anticipatory rather than reactive, aligning curricula with forthcoming regulatory milestones well before compliance deadlines. Third, India can leverage regional platforms such as BIMSTEC and IORA to share training expertise and build collaborative capacity across neighbouring maritime economies.

Ultimately, the effectiveness of these strategies will depend on translating policy commitments into sustained institutional investment, modernised curricula and robust enforcement of recruitment and welfare standards. If implemented coherently, India is well placed not only to meet global labour demand but also to shape the standards of the next generation maritime workforce.

5. Case Illustrations: Translating Policy into Practice

While regulatory debates on decarbonisation and digitalisation often remain abstract, several recent industry initiatives illustrate how these transitions are already reshaping day-to-day workforce requirements. These cases demonstrate that adaptation is neither theoretical nor distant; it is occurring now through targeted training, operational trials and cross-sector collaboration.

5.1 Alternative Fuel Readiness: Methanol Operations in Container Shipping

The commissioning of methanol-fuelled container vessels by Maersk in 2023 provides an early example of alternative-fuel integration at scale (Maersk, 2023). Prior to deployment, crews underwent specialised instruction covering methanol bunkering procedures, revised fire-fighting techniques, toxicity awareness and emergency response protocols. Unlike conventional fuels, methanol burns with a near-invisible flame and requires modified detection and suppression approaches, altering shipboard safety practices.

This case underscores that fuel transition is primarily a human transition. Even when propulsion technologies are available, safe operation depends on retraining officers and ratings in chemical hazard management and risk assessment. For labour-supplying nations, it signals that simulator upgrades and fuel-specific safety modules are now essential components of maritime education.

Ammonia Safety Pilots and Structured Competence Building

Mitsui O.S.K. Lines (MOL) has conducted controlled ammonia-handling pilots involving Japanese officers, focusing on leak detection systems, personal protective equipment, toxic exposure thresholds and emergency drills under supervised conditions (MOL, 2024). Given ammonia's high toxicity, even minor operational errors can have severe consequences.

These pilots highlight the value of staged competence development before commercial deployment. Rather than retrofitting skills after incidents occur, operators are embedding safety knowledge into training curricula in parallel with technology trials. The approach offers a replicable pathway for developing countries: begin with pilot simulations, develop standard operating procedures and progressively scale training as fleet adoption grows.

5.2 Cross-Sector Skilling: Cruise and Blue Economy Integration in India

Workforce transitions are not confined to fuels and automation alone. In India, collaboration between the Indian Maritime University and the Institute of Hotel Management has supported integrated training for cruise hospitality and service personnel (Press Information Bureau, 2023). This initiative broadens the conventional boundaries of maritime skills beyond deck and engine roles to include hospitality, safety awareness and passenger services.

The case illustrates an additional dimension of workforce strategy: diversification. By linking maritime training with cruise tourism and the wider blue economy, India can develop alternative career pathways and reduce over-dependence on conventional shipping segments. Cross-sector skilling may be particularly relevant for younger entrants and coastal communities seeking stable employment opportunities.

5.3 Lessons from the Cases

Taken together, the cases point to three consistent patterns. First, workforce preparation must precede technological adoption; training needs to lead, not follow, innovation. Second, new competencies are highly specialised and fuel- or system-specific, requiring targeted curricula rather than generic modules. Third, institutional collaboration—between industry, regulators and training providers - enables rapid implementation.

These illustrations reinforce the central argument of this paper: maritime transition is constrained less by technology or regulation than by human readiness. Nations that invest early in structured training ecosystems are more likely to capture emerging opportunities, while those that delay risk exclusion from higher-value segments of the global fleet.

6. Policy and Institutional Pathways

The preceding analysis demonstrates that workforce readiness is not an automatic by-product of technological change; it requires deliberate policy coordination, institutional investment and regulatory foresight. For labour-supplying nations such as India, reactive adaptation risks persistent skill gaps and competitive disadvantage. Instead, a proactive and structured approach is necessary to align training systems with the accelerating timelines of decarbonisation and digital transformation.

6.1 Curriculum Modernisation

Maritime Education and Training (MET) programmes must evolve beyond conventional STCW compliance towards anticipatory competence building. Modules on alternative fuels, hybrid propulsion systems, emissions monitoring, digital navigation tools and cyber-risk management should be embedded within mainstream curricula rather than treated as optional add-ons. Anticipating forthcoming revisions to the STCW framework and related IMO instruments will allow institutions to prepare graduates before regulatory mandates take effect. Early integration reduces retraining costs and strengthens employability in emerging vessel segments.

6.2 Simulation and Applied Safety Infrastructure

Classroom instruction alone is insufficient for managing the operational risks associated with methanol, ammonia or LNG. Practical competence requires exposure to realistic operating environments. Investment in bunkering simulators, engine-room mock-ups, and digital-twin laboratories can bridge this gap. Partnerships between the Indian Maritime University, ports, shipping companies and equipment manufacturers would enable shared facilities and cost-effective deployment. Such applied training environments enhance safety culture and allow officers to rehearse emergency scenarios before encountering them at sea.

6.3 Ethical Recruitment and Welfare Governance

Workforce expansion must be matched by strong governance. Persistent issues of fraudulent recruitment, excessive placement fees and crew abandonment undermine both seafarer welfare and India's reputation as a reliable labour supplier. Strengthened enforcement of the Registered Recruitment and Placement Service Licence (RPSL) regime, transparent placement records and digital tracking of contracts can reduce malpractice. Aligning these measures with the protections of the Maritime Labour Convention ensures that skill development is accompanied by dignity and security of employment.

6.4 Regional and Global Leadership

Beyond domestic reform, India is well placed to exercise regional leadership. Platforms such as BIMSTEC and the Indian Ocean Rim Association offer avenues for sharing training standards, faculty expertise and simulator access with neighbouring states. By positioning itself as a hub for maritime skilling and safety in the Global South, India can move from being primarily a labour supplier to a provider of knowledge and institutional capacity. Such leadership enhances both diplomatic influence and economic opportunity.

6.5 Regulatory Timeline and Workforce Implications

The urgency of these measures is underscored by the compressed regulatory horizon facing the industry. Table 2 summarises key milestones between 2023 and 2030, illustrating how environmental regulation, security events and labour standards converge within a single decade. For training institutions, each milestone effectively represents a deadline for competence development.

Table 2. Regulatory milestones and corresponding workforce implications (2023–2030)

Year	Regulatory / Industry Event	Workforce Implication
2023	IMO Revised GHG Strategy adopted; methanol vessels launched	Initial alternative-fuel training begins
2024	Red Sea disruptions; EU ETS phase-in	Higher operational risk; compliance monitoring skills required
2025	FuelEU Maritime enters into force; MLC amendments	Fuel reporting competence; welfare safeguards strengthened
2026	EU ETS full compliance; anticipated STCW updates	Formal curriculum revisions and certification changes
2030	IMO 40% carbon intensity checkpoint; large-scale alternative fuel adoption	Mass retraining and specialised fuel competence needed

Source: Compiled from IMO (2023, 2024), European Commission (2024), Reuters (2024).

Taken together, these milestones demonstrate that workforce planning cannot be incremental. Training cycles, infrastructure investment and regulatory coordination must proceed in advance of compliance deadlines. Countries that delay action risk shortages of certified personnel precisely when demand peaks.

In sum, policy and institutional pathways constitute the bridge between aspiration and implementation. Without systematic reform of curricula, infrastructure, governance and regional collaboration, the promise of a safe and equitable maritime transition will remain unrealised.

7. Conclusion

The analysis presented in this paper demonstrates that the maritime workforce is no longer a peripheral consideration within shipping policy but its central enabling condition. Decarbonisation targets, digital technologies and geopolitical disruptions are not abstract regulatory or technical developments; they translate directly into new competence requirements, altered risk profiles and evolving welfare needs for seafarers. In practice, the success or failure of the green and digital transition will depend less on hardware and regulation than on the preparedness of the people who operate ships and manage maritime systems.

The scale of change is substantial. Hundreds of thousands of seafarers are expected to require retraining in alternative-fuel operations, digital tools and cyber resilience within a single decade, even as persistent officer shortages constrain capacity. Without coordinated investment in education, simulation infrastructure and welfare governance, these pressures risk widening existing inequalities between shipowning and labour-supplying nations and undermining safety at sea.

Within this global landscape, India occupies a pivotal position. Its large and growing seafarer base, expanding institutional framework and policy momentum under Maritime India Vision 2030 provide a strong foundation for leadership. At the same time, uneven training quality, limited readiness for emerging fuels and weaknesses in recruitment governance remain structural constraints that require sustained reform. Comparative experience from the Philippines and China indicates that strategic coordination between training systems, labour deployment and industrial policy is critical for maintaining competitiveness in higher-value segments of the market.

The concept of a just transition offers a useful normative and practical lens for navigating these changes. Ensuring equitable access to training, protection from precarious employment and meaningful participation of seafarers in decision-making processes is not only a matter of fairness but also of operational effectiveness. A workforce that is skilled, secure and respected is more capable of supporting safe and sustainable shipping.

Ultimately, the strategic choice for India—and for other Global South labour suppliers - is whether to remain a quantitative provider of manpower or to evolve into a qualitative leader in maritime skills, safety and governance. By shifting emphasis from volume to value, investing in advanced training infrastructure and strengthening institutional oversight, India can position itself as a regional hub for maritime human capital. Such a transformation would secure livelihoods for its seafarers while enabling the broader objectives of decarbonisation, digitalisation and resilient global trade.

In this sense, the future of maritime sustainability is inseparable from the future of maritime labour. Placing the workforce at the centre of policy is therefore not optional but essential for the next phase of global shipping.

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Wind and Wave Power as a New Investment Horizon of the Marine Economy

Giorgi Rizhvadze[1]*

[1]Batumi State Maritime Academy, Georgia

* Corresponding author: giorgirijvadze@gmail.com

Abstract. This paper analyses offshore wind and wave energy as strategic investment assets within the Blue Economy framework. It examines technological maturity, investment dynamics, governance challenges and infrastructure requirements.

Offshore Wind and Wave Energy (OWE/WEC) represent a transformative investment horizon for the marine economy, driven by global decarbonisation imperatives and the commitment to triple renewable energy capacity by 2030. This paper examines the evolving investment landscape of offshore wind and wave energy within the framework of the Blue Economy, with particular attention to cost dynamics, technological maturity, grid infrastructure requirements and spatial governance challenges. Using qualitative policy and market analysis supported by secondary data from international energy agencies and financial institutions, the study evaluates the role of Floating Offshore Wind (FLOW) in unlocking deep-water resources and assesses wave energy's contribution to system resilience through its comparatively stable generation profile. The findings indicate that offshore wind has reached commercial competitiveness following a substantial reduction in levelised cost of energy, while wave energy, though at an earlier stage of development, offers high growth potential and strategic value for grid stability. The paper further demonstrates that large-scale deployment of OWE depends on coordinated investment in offshore grid infrastructure, meshed transmission systems and effective Maritime Spatial Planning to mitigate non-technical risks. The analysis concludes that offshore wind and wave energy constitute a central pillar of the Blue Economy, offering a long-term, resilient investment horizon for institutional capital aligned with sustainable economic growth.

Keywords: Offshore wind; Wave energy; Blue economy; Energy transition finance; Maritime spatial planning

1. Relevance of the Research Problem:

The global energy transition, driven by decarbonization commitments and the objective to triple renewable energy capacity by 2030, has significantly increased the strategic importance of marine renewable energy resources. Within this framework, offshore wind and wave energy have emerged as key components of the Blue Economy concept, which promotes the sustainable use of ocean resources for economic growth, environmental protection, and social development.

Although offshore wind energy has reached commercial competitiveness in many developed markets, wave energy remains at an earlier stage of technological and financial maturity. Furthermore, existing research predominantly focuses on large-scale projects in advanced economies, particularly in the North Sea and Baltic Sea regions, while transitional economies and semi-enclosed seas, such as the Black Sea, remain underrepresented in academic and policy discourse.

For Georgia, the relevance of this research is particularly pronounced due to several structural factors:

- Increasing dependence on imported energy resources;
- Significant but largely untapped offshore wind and wave potential in the Black Sea;
- Regulatory and institutional gaps concerning offshore renewable energy development;
- Limited access to domestic capital markets and specialized offshore infrastructure;

Under these conditions, an integrated and multidisciplinary assessment is required to evaluate technological feasibility, economic viability, environmental sustainability, and governance capacity. The study therefore addresses a critical research gap by analyzing offshore wind and wave energy as a strategic investment horizon within Georgia's marine economy.

2. Research Methodology

Our The research applies a mixed-method analytical framework combining qualitative and conceptual economic analysis. The methodology includes the following components:

A comprehensive review of international academic publications and institutional reports (IRENA, GWEC, OECD, NREL, and others) was conducted to assess technological maturity, cost dynamics (including Levelized Cost of Energy – LCOE), investment trends, and environmental impacts.

The study evaluates Georgia's existing legal and institutional framework governing renewable energy, with particular emphasis on offshore-specific regulatory gaps, permitting procedures, and marine spatial planning requirements.

International best practices from leading offshore wind markets (United Kingdom, Denmark, Germany, Netherlands) are analyzed to identify transferable policy instruments, financing mechanisms, and governance models applicable to emerging marine energy markets.

A conceptual evaluation of financial indicators (CAPEX, LCOE, NPV, IRR) and risk categories (technological, regulatory, financial, environmental, and market-related risks) was undertaken to assess investment attractiveness and project bankability. Georgia's Black Sea coastline is examined as an illustrative case to evaluate resource potential, infrastructure readiness, and development pathways within a transitional economy context. The study primarily relies on secondary data sources, international statistics, policy documents, and peer-reviewed literature. The analytical approach integrates qualitative assessment with selected quantitative indicators to ensure a holistic evaluation of offshore wind and wave energy development prospects.

3. Introduction

In recent decades, the global energy sector has undergone a profound transformation driven by increasing concerns over climate change, energy security, and sustainable economic development. The depletion of fossil fuel resources, combined with rising greenhouse gas emissions, has intensified the search for alternative and renewable energy sources. Within this context, marine-based renewable energy, particularly offshore wind and wave power, has emerged as a promising frontier in the transition towards low-carbon and resilient energy systems. Offshore wind farms and wave energy converters (WECs) have demonstrated substantial potential to contribute to national energy mixes while minimizing environmental impacts compared to conventional energy sources. From an investment perspective, offshore renewable energy projects represent capital-intensive but strategically significant assets.

4. Literature Review

Offshore wind energy has become one of the most mature and rapidly expanding sectors within the global renewable energy industry. Its development can be traced back to the early 1990s, when the first offshore wind farms were installed in Denmark and the Netherlands (Snyder & Kaiser, 2009). Compared to offshore wind, wave energy remains at a relatively early stage of technological and commercial maturity. Nevertheless, it is widely recognized as a promising renewable resource due to its high energy density and predictability (Falcão, 2010). Wave energy originates from wind-driven ocean surface movements, offering a complementary source to offshore wind systems. Offshore wind and wave projects are characterized by high upfront capital requirements, long payback periods, and complex financing structures (Politis et al., 2019).

Despite extensive international research, several gaps remain evident. First, most studies focus predominantly on offshore wind, while wave energy receives comparatively limited empirical attention. Second, integrated assessments combining technological, financial, and governance dimensions are still relatively rare. Third, transitional economies and semi-enclosed seas, such as the Black Sea, remain underrepresented in academic discourse.

Furthermore, existing literature often emphasizes large-scale projects in developed markets, neglecting small- and medium-scale deployment models suitable for emerging economies. As noted by Sovacool (2014), energy transitions are highly context-dependent and cannot be universally standardized.

By bridging global best practices with regional realities, the research seeks to advance both theoretical understanding and practical policy design.

Offshore wind energy represents the most technologically mature segment of marine renewable energy. Modern offshore wind turbines typically range from 8 MW to over 15 MW in capacity, allowing for higher energy yields and improved economic efficiency. Two main categories of offshore wind installations are distinguished in the literature: fixed-bottom and floating systems. Floating wind technologies have emerged as a strategic solution for deep-water environments where fixed foundations are technically or economically infeasible. Floating platforms, such as spar-buoy, semi-submersible, and tension-leg platforms, enable deployment in depths exceeding 60 meters (Myhr et al., 2014). These systems significantly expand the geographical scope of offshore wind development and are particularly relevant for regions with narrow continental shelves. Hybrid systems combining offshore wind and wave energy represent an emerging technological paradigm. Co-located wind-wave farms share common infrastructure, including foundations, electrical connections, and maintenance facilities. This integration reduces capital and operational costs while maximizing marine space utilization. Hybrid platforms integrating both turbines and WECs have also been proposed, particularly for floating structures. Energy storage technologies play a crucial role in supporting hybrid systems. Battery storage, hydrogen production via electrolysis, and compressed air energy storage enable temporal balancing between energy generation and demand. Offshore hydrogen hubs, in particular, are gaining attention as long-term storage and transport solutions.

Blended finance mechanisms combine public and private capital to improve project risk profiles. Green bonds and sustainability-linked loans have gained prominence as instruments for mobilizing long-term institutional investment (OECD, 2020). Public-private partnerships (PPPs) enable governments to leverage private-sector expertise while retaining strategic oversight. Such arrangements are especially relevant for port infrastructure, grid connection facilities, and pilot projects.

For transitional economies such as Georgia, economic and financial constraints remain a primary barrier to offshore renewable energy development. Limited domestic capital markets, high perceived country risk, and insufficient technical experience restrict access to competitive financing.

The economic and investment analysis demonstrates that offshore wind has reached commercial maturity, while wave energy remains in a transitional phase. Financial viability depends on technological reliability, regulatory stability, and access to diversified financing instruments. For emerging marine energy markets, coordinated policy support and innovative financing mechanisms are essential to unlock long-term investment potential. Life-cycle assessment studies indicate that offshore wind and wave projects exhibit relatively low carbon footprints compared to conventional power plants, even when accounting for manufacturing, installation, and decommissioning phases (NREL, 2020).

The development of offshore wind and wave sectors stimulates port modernization, logistics services, and technical training programs. These activities enhance human capital formation and foster innovation ecosystems in coastal regions. Furthermore, localized supply chains contribute to economic diversification and resilience. Indirect economic effects include increased tax revenues, tourism development linked to green branding, and improved energy security. For transitional economies, marine renewable energy may serve as a catalyst for structural transformation and international integration.

In the Georgian and Black Sea context, environmental and social considerations are particularly significant due to the ecological sensitivity of marine ecosystems and the economic importance of coastal tourism and fisheries.

Europe has emerged as the global leader in offshore wind deployment, with the North Sea and the Baltic Sea representing key growth hubs. Denmark, the Netherlands, Germany, and the United Kingdom have established large-scale offshore wind infrastructures that serve as benchmarks for technological and economic performance (GWEC, 2023).

Recent research highlights that hybrid offshore wind-wave energy systems can significantly improve marine space utilization, reduce infrastructure costs, and enhance overall energy production efficiency through shared platforms and grid connections (Zhang et al., 2024).

Furthermore, comprehensive assessments of the Black Sea indicate substantial untapped potential for both offshore wind and wave energy, supporting the region's strategic role in future renewable energy development and energy security (Silion & Rusu, 2025).

Recent spatial analyses also demonstrate that the Black Sea possesses favorable conditions not only for offshore wind generation but also for green hydrogen production, creating new opportunities for integrated offshore energy systems and long-term decarbonization strategies (Manolache & Onea, 2025).

The United Kingdom, for example, currently hosts over 10 GW of operational offshore wind capacity, supported by a robust regulatory framework, competitive auctions, and public-private partnerships (UK Government, 2022). These projects demonstrate the viability of large-scale deployment in deep waters and highlight successful integration of offshore wind into national energy markets.

Marine Renewable Energy Potential in Georgia Georgia possesses significant but largely untapped offshore wind and wave energy resources along its Black Sea coastline. Recent studies estimate the technical potential of offshore wind at approximately 1.2–2.0 GW within shallow coastal areas (Japaridze & Lomidze, 2019). Wave energy potential, although less quantified, is believed to offer substantial energy density due to consistent seasonal wave patterns, particularly between October and March (González et al., 2020).

The Georgian Black Sea coast benefits from moderate-to-high wind speeds averaging 6–9 m/s at 50 meters above sea level, which is sufficient for economically viable offshore wind projects. Wave heights typically range from 1.2 to 2.5 meters, offering moderate energy capture potential for point absorber and oscillating water column devices. These characteristics indicate the feasibility of small-to-medium scale offshore energy installations that can be progressively scaled up. Georgia’s legal and institutional framework for renewable energy development has made progress in recent years, yet offshore projects remain underdeveloped. Key regulations include the Law on Energy and Water Supply, Law on Renewable Energy, and licensing procedures governed by the Georgian National Energy and Water Supply Regulatory Commission (GNERC).

Despite challenges, Georgia has several strategic opportunities to develop marine renewable energy:

1. Pilot Projects: Deploy small-scale offshore wind and wave installations to demonstrate feasibility, reduce technological risk, and generate local expertise.

2. International Partnerships: Collaborate with experienced European and East Asian developers to leverage technical knowledge and financing.

3. Hybrid Systems: Integrate offshore wind and wave technologies to optimize energy yield and infrastructure use.

4. Blue Economy Integration: Use offshore energy development to support broader economic objectives, including port modernization, tourism, and coastal industrial growth.

5. Policy Innovation: Introduce auction mechanisms, green bonds, and long-term PPAs to enhance investment confidence. Key challenges for Georgia include:

Regulatory Gaps: Need for dedicated offshore licensing, environmental, and spatial planning policies.

Financial Risks: High CAPEX and limited domestic financing options.

Technical Barriers: Lack of specialized infrastructure, skilled labor, and operational experience.

Environmental and Social Risks: Potential conflicts with fisheries, tourism, and coastal ecosystems.

Market Uncertainty: Dependence on international energy prices and regional energy

Addressing these challenges requires an integrated approach combining institutional reform, capacity-building, stakeholder engagement, and strategic public-private investment planning.

Georgia's Black Sea offers a significant but largely unexploited opportunity for offshore wind and wave energy. While technical, financial, and regulatory challenges are substantial, lessons from global best practices suggest a phased, partnership-driven approach.

The following factors should be noted: Offshore wind technology is commercially mature, benefiting from standardized designs, floating platforms for deep waters, and advanced monitoring systems. Wave energy remains in the demonstration and optimization phase, yet presents substantial potential for hybrid systems and complementary energy production. Economic and Investment Feasibility Offshore wind projects demonstrate positive financial indicators (NPV, IRR, LCOE), while wave energy investments are more reliant on public funding and pilot initiatives. Hybrid wind-wave installations offer cost synergies, infrastructure sharing, and improved capacity utilization. Environmental and Social Sustainability

Final Remarks Offshore wind and wave energy represent transformative opportunities for Georgia's marine economy. By integrating technological innovation, economic viability, environmental stewardship, and social inclusivity, Georgia can establish itself as a regional leader in the blue economy.

The successful development of these resources requires coordinated action among policymakers, investors, researchers, and local communities.

5. Research Findings

The findings of this study confirm that offshore wind energy has evolved into one of the most technologically mature and commercially viable segments of the global renewable energy sector. Recent evidence demonstrates that continuous advancements in turbine technology, floating foundation systems, digital monitoring solutions, and economies of scale have substantially reduced the levelized cost of energy (LCOE), enabling offshore wind to compete effectively with conventional energy sources (Zhang et al., 2024). The emergence of floating offshore wind technologies further expands development opportunities in deep-water environments, significantly increasing the geographical scope of economically feasible offshore energy projects.

In contrast, wave energy remains at a comparatively early stage of commercial development. Although technological uncertainties and high capital costs continue to limit large-scale deployment, recent studies indicate that wave energy possesses considerable strategic value due to its high energy density, predictability, and complementary generation profile relative to offshore wind (Silion & Rusu, 2025). The research highlights that hybrid wind-wave systems can improve capacity utilization, enhance grid stability, reduce infrastructure costs through shared facilities, and increase overall project efficiency, making them a promising pathway for future marine energy development.

The analysis further reveals that investment attractiveness is strongly influenced by the quality of regulatory frameworks, long-term policy consistency, and access to diversified financing instruments. Offshore wind projects demonstrate robust economic performance under stable market conditions supported by competitive auctions, feed-in mechanisms, and long-term power purchase agreements. Conversely, wave energy technologies continue to require targeted public support, blended finance instruments, research funding, and risk-sharing mechanisms to overcome technological and financial barriers. The findings suggest that innovative financing models, including green bonds, public-private partnerships, and sustainability-linked investments, will play an increasingly important role in accelerating marine renewable energy deployment.

From an environmental and socio-economic perspective, offshore renewable energy contributes significantly to decarbonization objectives, energy security, and sustainable economic growth. Beyond greenhouse gas emission reductions, offshore wind and wave projects stimulate port modernization, local supply chain development, technological innovation, and employment creation in coastal regions. Recent studies also emphasize the growing role of offshore renewable energy in supporting green hydrogen production, thereby enhancing energy system flexibility and facilitating long-term climate neutrality objectives (Manolache & Onea, 2025).

In the Georgian context, the findings confirm that the Black Sea possesses substantial yet largely untapped offshore renewable energy potential. Available assessments indicate favorable wind resources and promising opportunities for future hybrid offshore energy systems. Nevertheless, the successful realization of this potential depends on addressing critical challenges, including regulatory fragmentation, limited infrastructure capacity, financing constraints, and insufficient technical expertise. The study demonstrates that a phased development strategy based on pilot projects, international partnerships, institutional reforms, and targeted investment incentives represents the most viable pathway for offshore renewable energy development in Georgia.

Overall, the research concludes that offshore wind energy is ready for large-scale commercial deployment, while wave energy is progressing toward commercialization through technological innovation and hybridization. The integration of these technologies within a comprehensive blue economy framework offers a strategic opportunity for Georgia to strengthen energy security, attract sustainable investment, accelerate decarbonization, and enhance its position within the emerging regional renewable energy market.

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Transport and Logistics Economics in The Context of The Caucasus and Türkiye: The Economic Effects of Infrastructure, Service Quality, and Regional Integration

Ayhan Salar [1*], Murat Koray [1*]

[1*] İstanbul Kent University, Türkiye

* Corresponding author: murat.koray@kent.edu.tr

Abstract. Transportation and logistics networks have a significant role in the improvement trajectories of developing and transition economies. These are particularly supported by growing processes and regional integration factors. Logistics performance has increasingly become related to economic decision-making across short, medium, and long-term horizons. This is beyond typical growth determinants like capital accumulation and labour input. This article will demonstrate how logistics parameters relate to regional and national integration, income growth, with an emphasis on Armenia, Azerbaijan, Georgia, and Türkiye, over the 2010–2024 period. The empirical evidence supports the dominant role of capital accumulation while suggesting that the logistics integrated variables do not exhibit a consistent short-term effect. Instead of short-term growth factors, results support an interpretation of logistics performance as a structural facilitator of improvement. These outcomes state the presence of adjustment costs and delayed transmission mechanisms related to logistic investment. Accordingly, logistics activities that appear neutral in the short term may generate cumulative economic benefits over extended periods. The study adopts a hybrid methodological approach that combines quantitative panel estimations with qualitative interpretation. Finally, the analysis highlights the limitations of existing perception-based logistics indicators in capturing short-term effects, while specifying their relevance as long run horizon decision support tools for policy makers pursuing logistics-oriented development strategies.

Keywords: Logistics, Economic Growth, Transport, Geoeconomics, Green Corridors

1. Introduction

The region has long been characterized as a bridge that offers access to core markets; this description is still analytically lacking. From a geoeconomic perspective, the region operates less as a passive transit space and more as an integrated logistics environment in which production, distribution, and consumption networks intersect. (Günay et al., 2025). Within this context, logistics performance—shaped by the quality of transport infrastructure and logistics services—assumes importance alongside traditional production factors such as capital accumulation and labour input. Its contribution is not typically observed through short-term cyclical movements, but rather through gradual and cumulative influences on long-term growth dynamics. (Yang et al., 2022). Through renovation, modernisation, and the integration of breakthrough technologies, logistics systems reduce operational costs, enhance market accessibility, and support the spatial diffusion of commercial activities (Li & Zhang, 2024; Alvarez-Palau et al., 2025). Viewing the Caucasus primarily as a corridor or transit route has delayed the recognition of logistics performance as a driver of development and, in turn, has also moderated the pace of economic growth (Gafarlı, 2025; Sharma & Dehalwar, 2025). Much of the existing literature approaches the Caucasus primarily through a transit-oriented lens, with an emphasis on corridor governance and institutional arrangements. As a result, the role of logistics performance itself—particularly as a determinant of long-term regional development—has received comparatively limited attention. Moreover, empirical contributions in this area often rely on cross-sectional data or short observation windows, restricting their ability to capture delayed or cumulative effects. (Harutyunyan, 2022), (Karchava et al., 2025), (Taisarinova, Loprencipe, & Junussova, 2020), (Chedia, 2024), (Hashimov, 2025). This study examines the impact of logistics performance on long-term and sustainable regional development, considering these restrictions. It accomplishes this by analysing a combination of logistics metrics, which encompass service quality, institutional efficiency, and operational effectiveness (Li, Radke, & Steimle, 2025), (Katamadze & Katamadze, 2023), (Prause, 2024). Within this framework, the study empirically examines whether logistics integration and improvements in logistics performance among Armenia, Azerbaijan, Georgia, and Türkiye exert an independent and statistically significant effect on regional economic growth (Deng & Noorliza, 2023), (Ukleba & Tsikhelashvili, 2021), (Abuselidze, 2021), (Raimbekov et al., 2018), (Brauweiler et al., 2023). The empirical analysis focuses on the relationship between logistics performance and income growth while explicitly accounting for capital accumulation and labour inputs. In addition, the study explores how logistics-related capabilities - such as transport mode optimisation, service quality improvements, and digitalization - are associated with regional logistics integration and broader economic performance. An extended production-function framework and panel data spanning the years 2010–2024 are used to analyze these problems. It is feasible to differentiate between short-term modifications and longer-term structural effects across different panel specifications by incorporating logistics performance into the growth model. The analysis is conducted within an extended production-function framework using panel data covering the period 2010-2024. This structure allows short-run adjustments and longer-term dynamics to be examined within a unified empirical setting. The following sections present the data construction procedures, empirical results, and their interpretation, before turning to policy implications and avenues for future research.

2. Theoretical Framework

2.1 Transport–Logistics and Economic Growth

In macroeconomic literature, classical factors such as capital, labour and technology are among the determinants of economic growth. However, transport and logistics infrastructure and service quality can also contribute to growth by interacting with these three elements. For example, various studies have shown positive relationships between logistics performance indices (Logistics Performance Index – LPI) and economic growth. For example, a study on the links between logistics performance and economic growth indicated that logistics performance makes a significant contribution to growth. (Journal of Social Sciences, 2025). At the country level, the effectiveness of logistics systems is commonly assessed using a limited set of internationally recognised composite indicators. Among these, the most frequently cited measures include the World Bank's Logistics Performance Index (LPI), the Agility Emerging Markets Logistics Index developed by Agility Logistics (Transport Intelligence, 2018), and the infrastructure-related "basic requirements" component of the Global Competitiveness Index published by the World Economic Forum (Schwab & Sala-i-Martín, 2017). In the present study, empirical analysis is based exclusively on the LPI dataset.

2.2 Infrastructure and Service Quality

Transport infrastructure (roads, railways, ports, air transport) forms the physical basis of the logistics system, while service quality (the competence of logistics companies, tracking and tracing systems, customs processes, the efficiency of border crossings) is a key factor determining the performance of the logistics system. For example, the report entitled 'Drivers of Logistics Performance' prepared by the International Transport Forum on Türkiye has revealed that service quality strongly influences logistics performance. (OECD, 2015)

2.3 Transit Corridors, Regional Integration and Logistics

Regional corridors (e.g. East-West, North-South axes) can increase trade by reducing logistics costs and transit times. The effective use of transport between modes plays an important role in reducing these transit times. This is stated as intermodal transport. In road-rail or sea-rail intermodal transport, transport documents are drawn up regarding the sharing of responsibility. (Salar A, 2017).. The effectiveness of these corridors is particularly important for the regional economy in geographically strategic areas. For example, concepts such as the 'Trans-Caucasus Transit Corridor' are mentioned in the literature in relation to the Caucasus. (World Bank, 2020)

2.4 Literature Specific to Türkiye and the Caucasus

It is stated that Türkiye's logistics sector has growth potential in terms of its strategic location, infrastructure investments, and service quality. For example, a study conducted on Türkiye indicates that the country's logistics and transportation sector is worth USD 100 billion and accounts for a significant share of GDP (V. International Caucasus-Central Asia Foreign Trade and Logistics Congress, 2019). (Worldbank,2019) There is a stable growth in Turkiye's transportation and logistics sector. Especially in the Caucasus, the literature indicates that Azerbaijan is developing its transport and logistics infrastructure, increasing its ongoing transit volumes, and struggling to transform its strategic location into a logistics hub.

3. Data Construction, Variable Transformation and Empirical Methodology

3.1 Panel Structure and Data Sources

The empirical investigation is conducted using an unbalanced annual panel at the country level, comprising Türkiye, Azerbaijan, Georgia, and Armenia for the 2010–2024 period. Standard macroeconomic indicators are obtained from the World Bank's World Development Indicators database, whereas logistics performance is captured through the Logistics Performance Index. Given the periodic availability of composite logistics measures and the inclusion of lagged explanatory variables, the usable sample is reduced to 60 country–year observations. The dataset is organised in a country–year format, allowing all variables to be treated within a common panel structure. This specification makes it possible to estimate growth-related models that incorporate country-specific fixed effects, thereby accounting for unobserved heterogeneity across economies while retaining the time-series variation necessary to examine the dynamic contribution of logistics performance to economic growth.

3.2 Construction of the Dependent Variable: Real GDP per Capita

Real GDP per capita, measured in constant 2015 U.S. dollars, is employed as the dependent variable to capture income dynamics in a manner that is comparable across countries and over time. In order to stabilize variance, improve functional linearity, and allow coefficient estimates to be interpreted in elasticity terms, the variable is transformed into its natural logarithmic form. Descriptive statistics for logged real GDP per capita, reported in Table 1, reveal pronounced cross-country dispersion alongside relatively moderate within-country variation over the sample period, underscoring the relevance of accounting for both structural heterogeneity and intertemporal dynamics in the empirical specification.

Table 1. Descriptive Statistics of Main Variables (2010–2024)

Variable	Observations	Mean	Std. Dev.	Min	Max
ln(GDP per capita)	60	8.6510	0.4603	7.9360	9.6256
ln(GFCF, constant)	60	23.3285	1.8069	21.3279	26.7399
ln(Labor)	56	15.3377	1.2137	14.1966	17.4013
ln(LPI)	24	1.0056	0.1375	0.7930	1.2556

Table 1 summarises the descriptive statistics of the variables used in the empirical analysis over the 2010–2024 period. Logged GDP per capita exhibits an average value of 8.65, accompanied by a standard deviation of 0.46, suggesting a relatively limited degree of dispersion within the sample. While variation across countries is evident, the range between minimum and maximum values reflects a broadly steady upward movement in income levels over time rather than abrupt fluctuations. All reported statistics are calculated by the author using the compiled dataset. (World Bank, 2020; World Bank, 2023; World Bank, 2024).

3.3 *Capital Variable and Inflation Adjustment*

Physical capital accumulation is proxied by gross fixed capital formation (GFCF). For Türkiye, Georgia, and Armenia, GFCF series are reported in constant prices, which permits direct comparison both over time and across countries. By contrast, Azerbaijan's GFCF data are available only in nominal terms. If used without adjustment, this would introduce price-level effects and distort cross-country comparisons within the panel. To ensure consistency, Azerbaijan's nominal GFCF series is therefore converted into real terms using the GDP deflator obtained from the World Bank's World Development Indicators (WDI). Accordingly, the real capital series is constructed as follows:

$$\mathrm{GFCF}_{it}^{const} = \frac{\mathrm{GFCF}_{it}^{current}}{\mathrm{GDP\ Deflator}_{it}/100} \quad (1)$$

Following deflation, the capital series is expressed in natural logarithms in order to maintain consistency of scale with the remaining production inputs and to allow coefficients to be interpreted as elasticities.

Evidence reported in Table 2, which contrasts nominal and deflated capital measures, illustrates the extent to which price movements—especially during periods of elevated inflation—distort the unadjusted series. Accounting for these effects is empirically important. When nominal capital values are used in preliminary estimations, the resulting coefficients exhibit clear instability and an upward bias, specifying that inflationary pressures rather than actual capital accumulation drive a substantial part of the estimated effect.

Table 2. Capital Stock Correction via GDP Deflator (Azerbaijan)

Year	**GFCF (Current Prices)**	**GDP Deflator**	**Real GFCF (2015=100)**
2010	nominal	158.59	deflated
2015	nominal	183.62	deflated
2020	nominal	253.32	deflated
2024	nominal	377.99	deflated

3.4 *Labor Input*

Labour input is represented by the total size of the labour force, using data obtained from the World Bank's World Development Indicators (SL.TLF.TOTL.IN). The series is aligned with the country–year panel structure and expressed in natural logarithms to remain consistent with the underlying production-function framework. As shown by the descriptive statistics in Table 1, labour force measures display considerably smoother dynamics than those observed for capital accumulation and income. This pattern points to limited short-run variability and suggests that labour input in the model essentially reflects longer-term demographic developments and labour market participation trends over the sample period.

3.5 *Annualization of the Logistics Performance Index*

The Logistics Performance Index (LPI), published by the World Bank, is available at irregular intervals (2010, 2012, 2014, 2016, 2018, and 2023), whereas the empirical strategy requires annual observations for panel data estimation. To reconcile this temporal mismatch, an explicit annualization procedure is implemented. Observed LPI scores are first structured in wide format and subsequently reorganized into a country–year panel. Missing annual values are then constructed through linear interpolation between adjacent benchmark observations, thereby generating a continuous annual series that preserves the underlying medium-term trend in logistics performance while avoiding the imposition of short-run volatility not supported by the data.

$$LPI_{i,t+k} = LPI_{i,t} + \frac{k}{T}\left(LPI_{i,t+T} - LPI_{i,t}\right) \tag{2}$$

Here, T represents the interval between two consecutively reported LPI benchmark observations. For boundary years at the beginning and end of the sample, forward- and backward-propagation procedures are employed to complete the annual series. The resulting country-specific logistics performance trajectories are subsequently transformed into natural logarithmic form to ensure consistency with the production-function specification and to facilitate elasticity-based interpretation. Interpolated LPI paths for each country are illustrated in Figure 1, while descriptive statistics reported in Table 3 document changes in the distributional properties of the series before and after annualization. The interpolation procedure increases within-country temporal variation relative to the original benchmark-only series, thereby strengthening parameter identification in fixed-effects regression frameworks. At the same time, Figure 1 underline pronounced cross-country heterogeneity in logistics performance dynamics: Türkiye exhibits higher average levels accompanied by greater intertemporal volatility, whereas Georgia displays a comparatively stable logistics trajectory over the sample period.

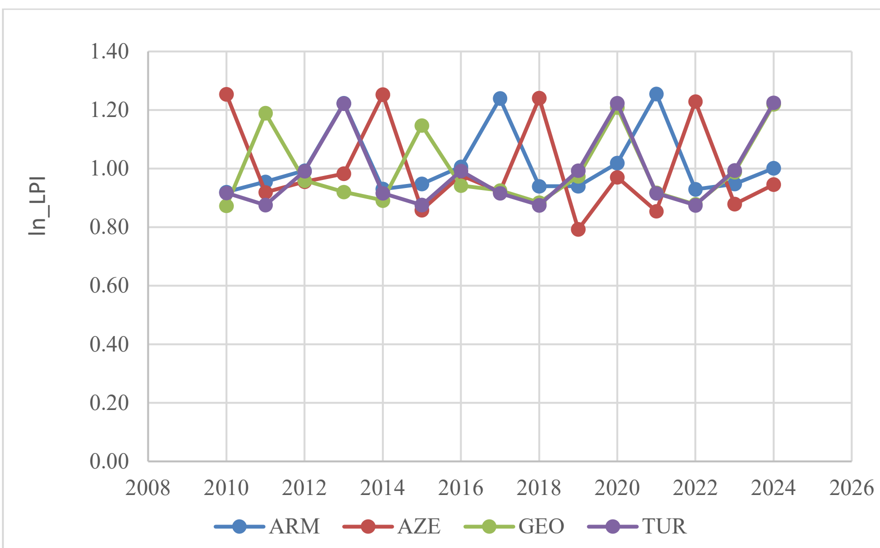

Figure 1. Interpolated ln (Logistics Performance Index) by Country, 2010–2024 (Compiled by author)
Notes: Annual values are obtained via linear interpolation between World Bank benchmark LPI survey years. The figure displays the natural logarithm of the interpolated series.

Table 3 confirms that annualization increases within-country temporal coverage without altering relative logistics performance rankings.

Table 3. LPI Coverage Before and After Annualization

Country	Observed LPI Years	Annualized Years	Mean ln (LPI)
Armenia	6	15	0.94
Azerbaijan	6	15	0.96
Georgia	6	15	0.95
Türkiye	6	15	1.22

3.6 *Baseline Econometric Specification*

Economic growth was modeled using an extended Cobb–Douglas production framework:

$$\ln(Y_{it}) = \beta_0 + \beta_1 \ln(K_{it}) + \beta_2 \ln(L_{it}) + \beta_3 \ln(Lg_{it}) + \mu_i + \varepsilon_{it} \quad (3)$$

Country fixed effects (μ_i) were incorporated to control for unobserved, time-invariant heterogeneity. Table-4 presents baseline pooled OLS and country fixed-effects estimates, demonstrating that failure to control for country heterogeneity leads to biased and unstable coefficient estimates.

Table 4. LPI Coverage Before and After Annualization

Variable	Pooled OLS	Country FE
ln(GFCF_const)	**0.296***	**0.340***
ln(Labor)	- 0.063	0.554
ln(LPI)	- 0.219	**- 0.860**
Constant	2.934	- 6.213
Country fixed effects	No	Yes
Observations	60	60

Note: * *** p<0.01, ** p<0.05

Interpretation of notations regarding significance factors are depicted in Table 5.

Table 5. Notation and Interpretation Table

Notation	Significance Level	Interpretation
***	$p < 0.01$	Strong statistical evidence at the 1% significance level
**	$p < 0.05$	Statistically significant at the 5% significance level
*	$p < 0.10$	Weak statistical significance at the 10% level
-	$p \geq 0.10$	Not statistically significant

As reported in Table 4, capital accumulation exhibits a positive and statistically significant elasticity across both pooled and fixed-effects specifications, while logistics performance enters with a negative coefficient once country heterogeneity is controlled for. (Compiled by author)

3.7 *Lagged Logistics Performance and Adjustment Dynamics*

Given the investment-intensive nature of logistics reforms, contemporaneous effects were not presumed. Accordingly, logistics performance was introduced with a one-period lag:

$$\ln(Y_{it}) = \beta_1 \ln(K_{it}) + \beta_2 \ln(L_{it}) + \beta_3 \ln(Lg_{i,t-1}) + \mu_i + \varepsilon_{it} \quad (4)$$

A statistically significant negative coefficient on lagged logistics performance is shown by the estimation results, which are presented in Table 6. This finding implies that short-term productivity gains may be outweighed by initial adjustment costs and fiscal pressures resulting from improvements in logistics infrastructure and procedures.

Table 6. Fixed Effects Model with Lagged Logistics Performance

Variable	FE + ln(LPI_{t-1})
ln(GFCF_const)	**0.349***
ln(Labor)	**0.668**
ln(LPI_{t-1})	**- 1.280***
Constant	- 7.644
Country fixed effects	Yes
Observations	56
Adjusted R²	**0.94**

3.8 Two-Way Fixed Effects and Common Shocks

To isolate logistics-specific effects from global and regional shocks, year fixed effects were added to the model:

$$\ln(Y_{it}) = \beta_1 \ln(K_{it}) + \beta_2 \ln(L_{it}) + \beta_3 \ln(Lg_{i,t-1}) + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

When time effects are taken into account, the logistics coefficient loses statistical significance, according to the corresponding results, which are compiled in Table 7. This outcome suggests that a non-trivial portion of the observed variation in logistics performance is associated with common time-specific shocks—such as global economic downturns and geopolitical disruptions—rather than solely with country-specific structural factors.

Table 7. Two-Way Fixed Effects Results (Country and Year)

Variable	Two-Way FE
ln(GFCF_const)	**0.248***
ln(Labor)	- 0.215
ln(LPI_{t-1})	0.236
Country FE	Yes
Year FE	Yes
Observations	56
Adjusted R²	**0.99**

Note: * *** p<0.01, Dependant variable: ln(GDP per capita)

The ln(GFCF_const) variable is found to be statistically significant at the 1% level with a positive coefficient *(b =0.248)* . This finding indicates that increases in capital investment are linked to statistically significant increases in the per capita income levels of nations. Given the logarithmic specification of the model, a 1% increase in capital accumulation is interpreted as being associated with an approximate 0.25% increase in per capita income. In contrast, although the labour variable (ln(Labour)) has a negative coefficient, it is not statistically significant. This indicates that, when controlling for country and year fixed effects, an increase in labour does not have a reliable effect on income levels. The absorption of unobservable factors such as demographic structure and labour force quality by fixed effects may have contributed to this result. The lagged value of the logistics performance index ($\ln(LPI_{t-1})$) also has a positive coefficient but is not statistically significant. Although this finding implies that improvements in logistics performance could potentially contribute to economic growth, it shows that when country-specific, time-invariant structural characteristics (such as geographical advantages, infrastructure legacy, and institutional structure) are controlled for, the effect of the LPI variable cannot be clearly distinguished. The adjusted R^2 value of the model, being 0.99 is characteristic of two-way fixed effects models, as the country and year dummies explain a very large portion of the variation in the data set. Therefore, the interpretation of the coefficients is based on 'changes over time within countries. Overall, the findings indicate that capital accumulation is a meaningful and strong determinant of economic growth, while labour and logistics performance variables do not showa significant effect when fixed effects are controlled.

3.9 Growth-Oriented Specification: First Differences

First difference specification was estimated in order to distinguish level effects from growth dynamics:

$$\Delta\ln(Y_{it}) = \gamma_1 \Delta\ln(K_{it}) + \gamma_2 \Delta\ln(L_{it}) + \gamma_3 \Delta\ln(Lg_{it}) + u_{it} \tag{5}$$

Growth regression results are reported in Table 8. Results in Table-8 indicate that improvements in logistics performance are positively associated with growth rates, although the effect remains statistically weak in the short run.

Table 8. Growth Regression (First Differences)

Variable	**Δln Model**
Δln (GFCF_const)	**0.102***
Δln (Labor)	0.285
Δln (LPI)	0.231
Constant	0.032
Observations	52
R^2	**0.26**

Note: * *** $p<0.01$, Dependent variable: Δln(GDP per capita)

Capital growth remained positive and statistically significant, while changes in logistics performance entered with a positive but statistically weak coefficient. Figure 2 plots average logistics improvements against growth rates, visually reinforcing the absence of a strong short-run relationship.

Figure 2 displays the short-run association between year-to-year changes in logistics performance and economic growth. The scatter plot reveals a highly dispersed distribution of observations around zero, with no visible linear structure. The fitted regression line displays a slightly positive slope ($\beta \approx 0.223$), but its explanatory power is almost negligible ($R^2 = 0.0021$). It is therefore defined that annual enhancements in logistics performance are not associated with immediate growth responses. Rather, the economic impact of logistics performance is more plausibly transmitted through longer-term structural adjustments—such as improvements in corridor efficiency, the implementation of customs reforms, and the strengthening of multimodal connectivity—than through short-run variations captured by first-differenced specifications.

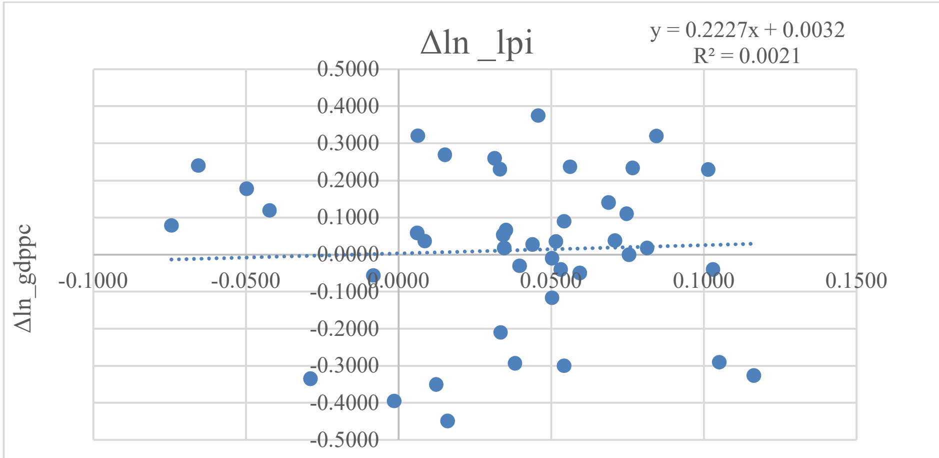

Figure 2. Short-run relationship between Δln(Logistics Performance Index) and Δln(GDP per capita)

4. Synthesis of Empirical Findings

Across all model specifications, capital accumulation is consistently identified as the primary determinant of economic performance. The contribution of labor input is found to be limited and does not display robust statistical significance. By contrast, logistics performance is shown to exhibit a non-linear and specification-sensitive association with economic growth: negative effects are observed in level-based models, statistical insignificance emerges once time effects are incorporated, and positive yet quantitatively modest effects are detected in growth-rate regressions. Table 8 synthesizes all model specifications and corresponding coefficient estimates, underscoring the sensitivity of logistics-related findings to choices regarding data construction, temporal structure, and econometric specification.

5. Implications and Research Limits

The findings and results suggest that logistics performance should not be interpreted as an automatic or immediate driver of economic growth in transition economies. Rather, its outcomes appear to be conditional upon investment cycles, adjustment frictions, and broader macroeconomic circumstances. Notwithstanding extensive data transformation and rigorous model testing, certain limitations remain, primarily due to the perception-based character of the Logistics Performance Index and the limited cross-sectional scope of the sample. Future research may be enhanced through the use of disaggregated logistics indicators, the inclusion of broader regional samples, and the application of dynamic panel estimation techniques.

6. Findings and Results

The major findings indicate that logistics performance should not be interpreted as an automatic or immediate engine of economic growth in transition economies. Instead, its economic effects appear to be contingent upon investment cycles, adjustment frictions, and broader macroeconomic conditions. Despite extensive data transformation and rigorous model testing, certain limitations persist, primarily reflecting the perception-based nature of the Logistics Performance Index and the limited cross-sectional dimension of the sample. Future research could be strengthened through the use of disaggregated logistics indicators, the expansion of regional coverage, and the application of dynamic panel estimation techniques. Once unobserved country-specific heterogeneity is controlled for through fixed-effects estimation, the coefficient associated with logistics performance becomes negative and statistically significant, pointing to the presence of short-run adjustment costs. These costs are likely to stem from infrastructure investment burdens, regulatory restructuring, and transitional inefficiencies accompanying logistics system upgrades. When time fixed effects are introduced, the statistical significance of logistics performance dissipates. This outcome suggests that logistics indicators are highly synchronized with common regional or global shocks—such as trade decelerations, geopolitical tensions, and pandemic-related disruptions—thereby constraining their independent explanatory power in contemporaneous regressions. Additional insight into the temporal structure of logistics effects is obtained by introducing a lagged logistics performance variable. The lagged specification yields a statistically significant negative coefficient, implying that initial improvements in logistics performance may impose short-term economic costs before productivity-enhancing benefits materialize. This pattern is consistent with adjustment-cost dynamics and learning-by-doing mechanisms widely discussed in the infrastructure and institutional reform literature. Finally, growth regressions based on first-differenced variables confirm the absence of a robust short-run relationship between logistics performance and income growth. Although the estimated coefficient on changes in logistics performance is positive, it remains statistically weak and explains virtually none of the observed variation in growth rates. This conclusion is further supported by the graphical evidence presented in Figure 2, which reveals a highly dispersed association with negligible explanatory power. A summary of empirical findings across all model specifications is presented in Table 9.

Table 9. Summary of Empirical Findings Across Model Specifications

Model Specification	ln(K)	ln(L)	ln(LPI) / Δln(LPI)	Interpretation of Results
Pooled OLS				Uncontrolled correlations; reflects raw associations rather than causal effects
Fixed Effects (Country)				Evidence of short-run adjustment costs associated with logistics improvements
Two-Way Fixed Effects (Country + Year)				Common time shocks dominate; logistics effects are absorbed by year effects
Fixed Effects with Lagged LPI				Delayed negative impact consistent with investment and reform costs
Growth Model (First Differences)				Positive but statistically weak short-run association

7. Conclusion and Recommendations

The nature of the connection between logistics performance and economic growth in economies that are developing regions is the subject of this study. Capital accumulation, labour input, and logistics performance are considered within a holistic analytical framework. The central conclusion is that logistics performance should not be interpreted as a short-run trigger of economic growth, but rather as a structural facilitator whose economic effects accumulate gradually over time. Adjustment costs, institutional learning processes, and economic actor coordination are all intrinsic to investments in logistics infrastructure, regulatory frameworks, and service quality. As a result, the contribution of logistics performance to economic growth materializes not in the short term, but gradually over the long run. From a policy point of view, it is more convenient to view logistics reforms as long-term strategic investments that operate in conjunction with capital formation, institutional quality, and macroeconomic stability. In this context, strengthening logistics systems in transition economies does not produce immediate and pronounced effects on short-term growth indicators; instead, it plays a complementary role by supporting trade facilitation and the transformation of production structures.

The difficulty of obtaining meaningful and consistent results from short-run panel analyses based on perception-based logistics indicators also highlights the methodological boundaries of this study. Future research would benefit from the use of more disaggregated logistics measures, dynamic model specifications, and longer analytical horizons, which would allow the delayed and cumulative contribution of logistics to economic growth to be captured more effectively. Overall, this study contributes to the literature by emphasizing that logistics performance should be conceptualized not as an immediate catalyst for economic growth, but as a strategic enabler and accelerator, a long-term prerequisite for economic development.

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Green and Sustainable Investments in Shipping in Asia

Bhavana Venkata Ramalingeswara Rao[1]*, Amritha Chanassery Sarasan

[1] Indian Maritime University, India

*Corresponding author: drbvrlrao@imu.ac.in

Abstract. Asia's dominant role in global maritime trade places the region at the centre of both shipping-related greenhouse gas emissions and the financing challenge associated with achieving the International Maritime Organisation's net-zero emissions target by 2050. Decarbonising the maritime sector is estimated to require investment exceeding USD 1 trillion, underscoring the critical role of sustainable finance. This paper examines how green shipping corridors function as a financial structuring mechanism to reduce investment risk and mobilise capital for low-carbon maritime assets in Asia. Using a qualitative research approach based on policy analysis and case evidence from India, Singapore, and China, the study finds that corridor-based development enhances project bankability by aggregating demand, improving regulatory certainty, and enabling climate-aligned financing. Financial instruments such as green bonds, blended finance, sustainability-linked lending, and public–private partnerships — aligned with the Poseidon Principles — emerge as key enablers of maritime decarbonization. The paper contributes to sustainable finance and maritime economics literature by positioning green shipping corridors as the operational nexus linking climate policy, financial markets, and measurable decarbonization outcomes.

Key words: Green shipping, green finance, green corridors, green bonds, Decarbonization

1. Introduction

Asia dominates global maritime trade, accounting for a substantial share of vessel traffic, shipbuilding capacity, and port throughput. This central role also positions the region as a significant contributor to shipping-related greenhouse gas emissions, intensifying the urgency for maritime decarbonisation in line with the International Maritime Organization's net-zero emissions target by 2050. While technological pathways for low- and zero-carbon shipping are advancing, their large-scale deployment remains constrained by high capital intensity, infrastructure requirements, and financial risk.

Estimates suggest that achieving maritime decarbonization will require investments exceeding USD 1 trillion by mid-century, highlighting the decisive role of sustainable finance. In response, green shipping corridors have emerged as a strategic instrument capable of aligning regulatory certainty, infrastructure development, and capital mobilization along designated maritime routes.

This paper analyses the role of green shipping corridors in enabling green and sustainable investments in Asian shipping. Focusing on India, Singapore, and China, it examines how policy frameworks, financial instruments, and public–private partnerships interact to improve investment bankability and accelerate maritime decarbonization.

The primary objective of this study is to evaluate the structural role of Green Shipping Corridors in mitigating financial risks associated with maritime decarbonization and to examine how these corridors function as catalysts for mobilising climate-aligned investments within the Asian maritime sector

China, Singapore, and Japan were selected for this study because they represent leading maritime economies in Asia with significant influence on global shipping activities, port infrastructure development, technological innovation, and the implementation of sustainability initiatives. These nations have also demonstrated active participation in adopting IMO decarbonization strategies and green financing mechanisms

2. Literature Review and Conceptual Framework

Existing literature on green shipping primarily focuses on technological pathways for reducing maritime emissions, including alternative fuels, vessel efficiency improvements, and operational optimization. Studies identify fuels such as liquefied natural gas, green hydrogen, ammonia, and methanol as critical to achieving lifecycle emissions reductions, while also highlighting challenges related to fuel availability, infrastructure readiness, and safety standards.

More recent scholarship introduces green shipping corridors as a mechanism to operationalize maritime decarbonization by concentrating policy coordination, infrastructure investment, and technological deployment along specific routes. These corridors translate global climate ambitions into localized, demonstrable action. However, existing studies often treat corridors primarily as policy or technology pilots, with limited emphasis on their financial structuring role.

Parallel research in sustainable finance emphasizes the growing importance of green bonds, sustainability-linked loans, and climate-aligned lending frameworks such as the Poseidon Principles in shaping maritime investment decisions. While these instruments promote emissions-aligned portfolios, their interaction with corridor-based development, particularly in the Asian context, remains underexplored, forming the central research gap addressed in this study.

While existing studies focus on technological pathways, limited attention is paid to how financial instruments are operationalized through corridor-based mechanisms

Conceptual Framework. Four pillars are the shipbuilding financial assistance scheme, the Maritime development fund, Ship building development scheme.

3. Research Methodology

This study adopts a qualitative and descriptive research design to examine green and sustainable investment trends in Asian shipping. The methodology comprises:

1. Systematic literature review of peer-reviewed journals, IMO reports, policy documents, and sustainability frameworks.

2. Thematic analysis of green finance instruments, policy initiatives, and green corridor developments across Asia.

3. Case study analysis focusing on India, Singapore, and China to assess the interaction between policy support, investment mechanisms, and decarbonisation outcomes.

Secondary data sources include reports from the IMO, World Bank, Maritime and Port Authority of Singapore, Government of India policy documents, and sustainability disclosures from shipping companies and financial institutions.

This study adopts a qualitative research design based on comparative policy analysis and thematic content analysis using secondary sources such as IMO reports, academic literature, policy documents, and sustainability reports.

4. Asia Context: Key Initiatives and Infrastructure

Asian maritime policy frameworks have expanded significantly in response to increasing decarbonisation pressures and evolving global climate commitments. Several leading economies, including South Korea, Vietnam, and Singapore, have implemented policy measures to support fleet retrofitting, energy-efficient shipbuilding, and the adoption of alternative fuels. These initiatives increasingly align national maritime strategies with long-term emissions reduction pathways and investment-led sustainability transitions.

India. India has undertaken a strategic transformation of its shipbuilding and maritime ecosystem, emphasizing low-carbon technologies, alternative fuels such as green ammonia and methanol, and the digitalization of ports and logistics systems. Regional integration forms a central pillar of India's approach, exemplified by initiatives such as the India–Singapore Green and Digital Shipping Corridor, which combines regulatory coordination, infrastructure development, and investment facilitation along key trade routes. China, while maintaining global leadership in shipbuilding capacity, continues to face high absolute emissions due to the scale of its maritime and industrial activities, reinforcing the need for efficiency improvements and progressive fuel transition strategies.

Singapore. Singapore has positioned itself as a regional leader in sustainable maritime development through coordinated investments in clean bunkering infrastructure, port electrification, and advanced digital port systems. Its long-term commitment to carbon neutrality by 2050 is supported by targeted financial incentives and dedicated research institutions focused on low- and zero-carbon maritime technologies, strengthening its role as a hub for green shipping finance and innovation.

These partnerships play a critical role in reducing investment risk, crowding in private finance, and facilitating the knowledge transfer necessary to overcome technological and financial barriers.

Within this regional context, green shipping corridors function as the operational nucleus of a circular ecosystem linking climate policy, sustainable finance, and technological deployment. Policy frameworks provide regulatory certainty, financial mechanisms enable capital mobilisation, and infrastructure and vessel investments deliver measurable decarbonisation outcomes. These outcomes, in turn, reinforce investor confidence and regulatory support, creating a self-reinforcing pathway toward maritime net-zero emissions in Asia. Singapore represents a finance-led corridor model, whereas India follows a policy-driven public investment approach.

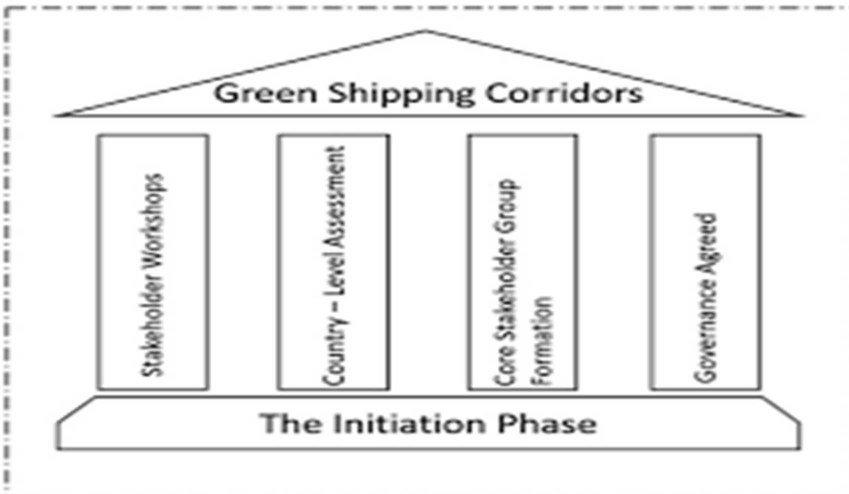

Figure 1. Conceptual Framework of Green Shipping Corridors in Asia

Figure 2 Illustrates the integrative role of green shipping corridors as a financial and policy coordination mechanism for maritime decarbonisation in Asia.

Figure 2. Conceptual Framework of Green Shipping Corridor Finance Ecosystem

The framework is structured around four interlinked pillars:

A conceptual framework figure illustrating the relationship among climate policies, Green Shipping Corridors, financial mechanisms, and sustainable outcomes has been added.

1. Policy and Regulation: National maritime policies, IMO decarbonisation targets, fuel standards, and corridor-level regulatory alignment provide long-term policy certainty.

2. Sustainable Finance Mechanisms: Green bonds, blended finance, sustainability-linked loans, and public-private partnerships aligned with the Poseidon Principles mobilise capital and reduce investment risk.

3. Technology and Infrastructure Deployment: Investments in alternative-fuel vessels, bunkering infrastructure, port electrification, and digital systems enable operational decarbonisation along corridor routes.

4. Decarbonisation outcomes and market confidence: measurable emissions reductions, transparent reporting, and improved asset performance enhance investor confidence and reinforce regulatory support.

The circular interaction among these pillars demonstrates how green shipping corridors create a self-reinforcing investment ecosystem, enabling scalable and bankable pathways toward maritime net-zero emissions in Asia.

5. Investment Opportunities in Asian Shipping

IMO's Marine Environment Protection Committee sent an ambitious new target in July 2023 to achieve net-zero emissions by 2050. The major objective is to increase the demand for vessels that use cleaner fuels, which are less carbon-intensive.

The Poseidon Principles, one of the most pivotal initiatives, which was launched in 2019, is also a framework that was meant for measuring and reporting how well the financial institutions' shipping portfolio aligns with climate targets. These principles are a global framework of financial institutions, including lenders, lessors and guarantors, to assess and disclose the climatic alignment of their ship portfolios with the International Maritime Organization's decarbonisation targets.

The framework comprises four principles: assessment of climate alignment, accountability for reporting progress, enforcement through internal transparency, mechanisms and public disclosure of results. These carbon emissions are measured and evaluated against the decarbonisation trajectories established by IMO. These principles actually promote green shipping by favouring low-emission vessels with finance portfolios. This helps to strengthen the decarbonisation mechanisms in the Asian sector.

Financial mechanisms like green bonds and public-private partnerships play a crucial role by funding the infrastructure and technology upgrades. The green bonds are instruments that finance maritime decarbonisation by raising capital for sustainable projects like retrofits, alternative fuel adoption, port electrification, and emission monitoring systems. Lenders qualify vessels for green bond proceeds based on environmental performance metrics that align with the Green Bond Principles, EU Taxonomy, Climate Bonds Initiative and Poseidon Principles.

CRAs Asian economies heavily rely on maritime trade; shipping finance plays a crucial role. In Asia, corridors like China-Qingdao-Hamburg, India-Singapore, and Vietnam-Cai Mep links drive trade growth in China, India, and Vietnam, linking to the Poseidon Principles. In In India, the new corridors include the India Green Corridors, the India-Denmark Green Corridors, the India-Singapore and the Kandla-Tuticorin Coastal Green Corridor.

The Maritime and Port Authority of Singapore (MPA) has significantly accelerated its commitment with S$50 million to sustainable maritime practices under the Maritime Singapore Green Initiative (MSGI).

MSGI, which comprises five programmes:

Green Ship Programme. The revised Green Ship Programme (GSP) offers powerful financial incentives, providing up to a 100% concession on initial registration fees and annual tonnage taxes for vessels that meet stringent green criteria. To qualify, ships must either significantly exceed the IMO's Phase 3 EEDI standard, adopt low- or zero-carbon fueled technologies, alternative fuels and efficient vessel design.

There are various green shipping mechanisms in India to facilitate the transition to sustainable maritime operations.

Green bonds. Green bonds in shipping raise capital through debt instruments. These proceeds are exclusively used to finance or refinance projects in the maritime sector. These mechanisms follow rigorous certification standards to ensure that projects align with global climate targets. Green bonds have also become an attractive investment opportunity, as they are risk-adjusted returns compared to conventional bonds. Its yield is a combination of financial gain and social responsibility, which is now a rapidly expanding sector in Asia. In Asia, issuers like COSCO and Mitsui O.S.K. Lines use these instruments to finance environmentally friendly green projects like low-emission vessels and port infrastructure upgrades.

Blended Finance. On December 9, 2015, the Government of India approved the Financial Assistance Policy for Indian Shipyards. This was to provide financial assistance for shipbuilding contracts. India has allocated ₹69,725 crore to reinvigorate its shipbuilding and maritime ecosystem, recognizing the sector's strategic importance. India's four-pillar approach to maritime funding, part of a ₹69,725 crore package approved in September 2025 were:

Four-Pillar Framework for Green Shipping

Pillar 1: Shipbuilding Financial Assistance scheme - It being the cornerstone of India's maritime revival strategy, it allocated a substantial ₹24,736 crore. Its key objective is to provide direct financial assistance to offset the highest cost of construction in India when compared to foreign shipyards, thereby making Indian shipyards globally competitive. This scheme has also introduced a credit note mechanism, which establishes a direct financial bridge where the act of scrapping the old ship generates a credit that can be used to reduce the cost of the new ship.

Pillar 2: Maritime Development Fund – and financial institutions for loans to reduce the borrowing costs for maritime enterprises. It allocated ₹25,000 crore that is designed to enable long-term financing through equity and debt mechanisms in shipbuilding, shipyards, ports, and related infrastructure, with government contribution capped at 49% in a blended finance model. The Interest Incentivization Fund will have a corpus of ₹5,000 crore for a duration of 10 years. It will incentivise up to 3% to be provided to banks

Pillar 3: The Shipbuilding Development Scheme (SbDS)- with an allocation of ₹19989 will be utilized for establishing greenfield shipbuilding clusters. It also emphasises expanding the brownfield capacity to elevate the existing shipyards to 4.5 million GT. It also establishes the India Ship Technology Centre, which will be an apex body under the Indian Maritime University, which will be focused on research and development, Skill training and also technology transfer to put India as a shipbuilding innovator.

Pillar 4: Skilling & Technical Capability, Legal, Taxation, Policy Reform - It sweeps away roadblocks and fuels investments by overhauling laws, policies, and taxes, while building up worker skills with hands-on training, pushing forward R&D, sticking to top quality standards, rolling out green tech, and locking in robust safety measures. The Hong Kong International Convention (HKC), which mandates global environmental and safety standards for ship recycling, entered into force on June 26, 2025. India leads globally in compliance, with nearly 115 of its 130 ship recycling yards now meeting the HKC requirements.

The Table 1 synthesises regulatory frameworks, financial instruments, and national initiatives shaping investment opportunities in Asian shipping under the International Maritime Organisation's net-zero 2050 strategy. Monetary values are reported as per official government and institutional disclosures.

Table 1: Investment Opportunities in Asian Shipping Under the Decarbonization Framework

Green Shipping Corridors	Corridor-based decarbonization model	Aggregated demand, fuel availability, and regulatory clarity	Project finance, corridor-linked bonds	China–Qingdao–Hamburg, India–Singapore, Vietnam–Cai Mep	Accelerates zero-emission route deployment
MSGI – Green Ship Programme	Vessel incentives	Up to 100% concession on registration & tonnage tax	Capex incentives	Methanol, hydrogen, CII-A vessels	Encourages fleet modernization
MSGI – Green Port & Craft	Port & harbour craft decarbonization	Energy Efficiency Grants, clean harbour craft	Infrastructure finance	Port of Singapore	Cuts port-side emissions
Indian Policy Alignment	Maritime India Vision 2030	Low-carbon tech, shipbuilding revival	Policy-backed finance	India	Long-term maritime sustainability
Indian Long-term Vision	Maritime Amrit Kaal Vision 2047	Net-zero aligned maritime growth	Sovereign-backed funding	India	Structural decarbonization
India – Pillar 2	Maritime Development Fund	₹25,000 crore; blended equity & debt; 3% interest subsidy	Blended finance	Ports, shipyards, logistics	Lowers financing cost
India – Pillar 3	Shipbuilding Development Scheme	₹19,989 crore; greenfield clusters. India Ship Technology Centre	Infrastructure & R&D funding	Under Indian Maritime University	Builds innovation capacity
Circular Economy	Hong Kong International Convention (2025)	Global standards for safe & green ship recycling	Recycling infrastructure finance	India (115+ compliant yards)	Completes sustainable vessel lifecycle

6. Challenges and Barriers

Even though there is significant progress, the transition toward green shipping in Asia faces multiple challenges. High capital costs associated with alternative fuel vessels, retrofitting, and bunkering infrastructure still remain a primary barrier, mostly for small and medium-sized ship-owners. Uncertainty about fuel availability, particularly for green hydrogen, ammonia and methanol, restricts large-scale deployment beyond pilot corridors**.** Regulatory fragmentation across Asian jurisdictions further complicates implementation, as varying safety standards, fuel certification norms, and carbon pricing mechanisms contribute to compliance challenges. Technology maturity risks, including engine reliability and fuel storage safety, also affect investor confidence. In addition to it, limited access to affordable long-term finance limits the scalability of green shipping initiatives by economies. To manage these barriers, harmonised regulations, risk-sharing financial mechanisms, and coordinated public–private investment strategies are required.

Financial Barriers: High operational expenses and substantial upfront capital requirements create financial constraints within the maritime industry. These financial limitations represent the most significant obstacle to the adoption of sustainable initiatives in ports. It will take at least $1 trillion to invest in land-based infrastructure and ship -related technologies in order to reduce international shipping's greenhouse gas emissions in half by 2050.

Regulatory Challenges: Policy actions at national, regional and global levels are really important to achieve a net-zero pathway. This is especially true for transition finance which helps industries and economies move toward carbon neutrality. For this to happen, international organisations should work together to develop a framework. This will enable smooth integration across economies and more affordable funding options to overcome financial limitations.

Political Interventions: To reduce carbon emissions in the maritime industry, people with political views must agree on policies. Trade disputes and disagreements over energy are causing problems. This happens to slow down the process. As a result, short term energy security is often prioritised.

Operational and Technical Challenges: The global merchant fleet has a lot of ships, 105,493, to be exact that travel across the ocean. These ships are really big; they weigh 100 tonnes or more. Most of the merchant fleet still uses fossil fuels to move around. The global merchant fleet has a long life, usually between 25 to 30 years. So we must make changes to the merchant fleet a little bit at a time.

For existing vessels, the most straightforward approaches used to reduce energy consumption involve modest, low-cost modifications. Optimising vessel speeds through controlled reductions and air lubrication systems that minimise hull-water. Additional low-investment options such as streamlined routing, eco-friendly antifouling hull coatings to maintain cleanliness and proactive engine maintenance protocols, also increase efficiency. On the other hand, carbon capture technologies are a better option because they are more flexible. The reason is that alternative fuels require no changes to the structure of the engine, and they work with all types of fuel.

Low-carbon fuels and emission-free fuels are really expensive and hard to find, which is a problem for ship owners who want to switch to low-emission vessels. The thing is, these new fuels are still pretty new so there are a lot of questions about how to keep people safe, what to do in an emergency and how to be prepared for disasters. Ports all around the world are having trouble paying for the special equipment they need to store and give out this fuel to the green-fuel vessels. This is an issue for the green-fuel vessels and the companies that make green fuel.

These systematic challenges underscore a critical financing shortfall in the green shipping sector. Strategic investments deployed through mechanisms such as green bonds, sustainability-linked loans and blended finance provide an effective means to address it. Such instruments derisk the scaling of alternative fuel production, facilitate port infrastructure modernisation and promote multi-stakeholder coordination.

Infrastructure and Safety Challenges of Alternative Fuels in Asian Ports. Although alternative fuels such as Hydrogen and Ammonia are increasingly viewed as promising solutions for reducing carbon emissions in the maritime sector, their large-scale implementation presents significant infrastructure and safety challenges. Hydrogen requires specialized storage systems because of its low volumetric energy density and highly flammable nature. Similarly, Ammonia, despite its carbon-free combustion potential, is toxic and requires stringent handling procedures and dedicated storage infrastructure. Many Asian ports are currently in the early stages of developing bunkering facilities, safety standards, and emergency response systems for these fuels. Investments in port infrastructure, workforce training, and regulatory frameworks will therefore play a critical role in facilitating the successful transition toward green shipping

The SWOT analysis demonstrates that while each country possesses distinct strategic advantages, the successful implementation of green shipping initiatives requires balancing technological development, financial investment, and regulatory adaptation.

Table 2. SWOT table

Country	Strengths	Weaknesses	Opportunities	Threats
China	Strong government support; large shipbuilding capacity	High implementation cost; dependence on fossil-based infrastructure	Leadership in green technologies and alternative fuels	Regulatory complexity and economic fluctuations
Singapore	Global port connectivity; strong financial ecosystem	Limited land and natural resources	Expansion of green bunkering and maritime finance	Competitive regional ports
Japan	Advanced technological innovation; strong R&D capability	Aging workforce and high investment requirements	Development of hydrogen-based shipping technologies	Global market uncertainty and technology adaptation risks

7. Conclusion

Green and sustainable investments are rapidly reshaping the Asian shipping industry, positioning the region as a central driver of global maritime decarbonisation. The convergence of green shipping corridors, innovative financial instruments, and supportive policy frameworks has enabled measurable progress toward low-carbon maritime operations. Asia's experience demonstrates that coordinated action between governments, financial institutions, ports, and shipowners is essential to overcome cost, technology, and regulatory barriers.

India's policy-driven maritime financing model and Singapore's structured incentive-based approach provide replicable pathways for other emerging economies. As climate rules get tougher and investors demand more from companies on sustainability, green finance is turning into a make-or-break edge for shipping firms trying to stay ahead. Boosting teamwork across regions, aligning reporting standards, and ramping up investments in key shipping corridors are essential steps to hit the IMO's net-zero emissions target by 2050.

Future research Directions: the future research areas may be in the field of Quantitative finance modelling, corridor performance metrics, and Carbon pricing impacts

The transition toward sustainable maritime operations in Asia requires not only policy support and innovative financial instruments but also practical readiness in infrastructure and safety systems. The experiences of China, Singapore, and Japan suggest that integrated approaches involving technology, regulation, and investment strategies are essential for achieving long-term maritime sustainability goals.

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Developing Maritime Human Capital: The Role of Nautical Leadership and Motivation, Empirical Studies from Indonesian Seafarers

Niken Sitalaksmi Widjaja[1]*, Inayatur Robbany[1], Aliya Izet Begovic Yahya[1]

[1]Sekolah Tinggi Ilmu Pelayaran, Jakarta, Indonesia

*Correspondence authors: sitalaksmiw@gmail.com

Abstract. The maritime industry increasingly recognizes leadership competence as a critical factor in enhancing operational safety, crew performance, and organizational sustainability. However, empirical evidence examining how nautical leadership contributes to maritime human capital development, particularly through motivational mechanisms in developing maritime countries, remains limited. This study investigates the direct and indirect relationships between nautical leadership, motivation, and human capital among Indonesian seafarers. A quantitative explanatory design was employed using survey data collected from 350 seafarers enrolled in STCW-based leadership training programs at STIP Jakarta. Data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM) with SmartPLS 4.0. The findings demonstrate that nautical leadership has a strong positive effect on motivation (β = 0.974) and a significant direct effect on human capital (β = 0.481). Motivation also significantly enhances human capital (β = 0.505) and partially mediates the relationship between nautical leadership and human capital. The structural model exhibits substantial explanatory power, with R^2 values of 0.949 for motivation and 0.961 for human capital. These findings indicate that leadership competencies — including decision-making, team management, crisis communication, navigation leadership, and conflict resolution — not only strengthen seafarers' motivation but also improve their technical competence, adaptability, and career development. This study contributes to the maritime human capital literature by providing empirical evidence of the leadership–motivation–human capital relationship within Indonesian maritime education and offers practical implications for integrating leadership development and motivation enhancement into maritime education and training curricula.

Keywords: Nautical leadership; Motivation; Human capital; Seafarers; Maritime education; PLS-SEM; Indonesia.

1. Introduction

The development of leadership competencies has become increasingly essential in the contemporary maritime industry. According to Stopford (2020), "leadership skills are as critical as technical skills in ensuring maritime operational success." Leadership is now recognized as a vital determinant of safety, coordination, and crisis management at sea. Lee and Choi (2021) emphasized that "leadership training in maritime education significantly improves crew coordination and safety outcomes." Similarly, Theotokas and Progoulaki (2021) stated that "effective shipboard leadership enhances decision-making efficiency during critical situations." Persistent leadership gaps remain a global concern, with Bloor et al. (2020) noting that "leadership gaps remain a persistent challenge within global maritime labor." In line with this, Bhattacharya (2022) argued that "sustainable maritime operations require continuous investment in human capital leadership development," underscoring the relevance of leadership training in modern maritime education.

Indonesia, as the world's largest archipelagic nation, faces unique challenges in maritime human resource development. The Ministry of Transportation (2023) reports that "the national shipping sector demands 40,000 new qualified officers annually to meet economic growth targets." However, leadership development has not progressed at the same pace as technical training. Widyaningrum et al. (2022) found that "maritime education institutions in Indonesia often emphasize technical skills at the expense of leadership competencies." Wahyudi et al. (2022) similarly observed that "graduates from Indonesian nautical academies report gaps in leadership and soft-skills training." The World Maritime University (2021) stressed that "developing leadership among seafarers is essential to bridge operational and managerial performance gaps." Reflecting the same concern, Antara News (2024) highlighted that "Indonesia's seafarers must enhance leadership readiness to compete globally."

On a global scale, the maritime sector continues to confront shortages of competent leaders. According to the BIMCO/ICS Seafarer Workforce Report (2021), "a shortage of 89,510 officers is projected by 2026, largely due to leadership skill deficiencies." Modern maritime operations increasingly require leadership competencies beyond traditional technical expertise. Cahoon et al. (2023) asserted that "modern maritime operations demand leadership competencies beyond traditional technical expertise." Evidence also shows that leadership styles matter, with Chia et al. (2022) reporting that "crew performance improves significantly under transformational leadership styles." The International Transport Workers' Federation (ITF, 2023) emphasized that "investing in leadership training is key to seafarer retention and welfare." Furthermore, Parola et al. (2023) argued that "future maritime leaders must be equipped to manage digital and sustainable shipping transformations," aligning leadership requirements with global technological shifts.

Leadership training in maritime education is increasingly regulated by both national and international standards. Indonesian Ministerial Regulation No. 65/2020 mandates that "nautical education curricula must include leadership and management training" (Ministry of Transportation, 2020). At the global level, the STCW Convention (1978, as amended) requires that "officers demonstrate leadership and teamwork competence" (IMO, 2021). Complementing this, the Maritime Labour Convention (MLC, 2006) highlights that "seafarers have a right to career development and leadership opportunities" (ILO, 2019). More recently, Presidential Regulation No. 25/2024 reinforces Indonesia's alignment with IMO standards in maritime competence development. Wu and Yan (2023) emphasized that "regulatory compliance necessitates the formal integration of leadership training within seafarer education programs," signaling the growing importance of leadership-focused instruction.

Nautical education institutions play a central role in shaping maritime leadership competencies. As Theotokas and Progoulaki (2021) noted, “maritime academies are pivotal in shaping the leadership abilities of future officers.” To meet shifting industry demands, curriculum modernization has become essential; Bloor et al. (2020) highlighted that “curriculum modernization is critical to meeting the evolving leadership demands of the maritime industry.” Hands-on leadership training has also proven effective, with Wahyudi et al. (2022) demonstrating that “practical leadership training significantly enhances graduates’ readiness for shipboard responsibilities.” Chinomona and Sandada (2022) further argued that “context-specific education programs can close gaps between technical expertise and leadership skills.” According to Sekaran and Bougie (2022), “structured interventions in education are effective in building complex leadership competencies,” reinforcing the need for pedagogical reform.

Leadership training is a critical driver of maritime human capital development. Stopford (2020) argued that “human capital quality determines the safety, efficiency, and competitiveness of maritime operations.” Similarly, Bhattacharya (2022) observed that “training interventions improve both technical performance and leadership capacity.” Lee and Choi (2021) found that “leadership training leads to better emergency decision-making among ship officers,” strengthening operational resilience. Widyaningrum et al. (2022) emphasized that “leadership development programs positively correlate with employee loyalty and retention in maritime contexts.” Moreover, Kusuma et al. (2022) demonstrated that “organizational competence improves when leadership training is systematically embedded in development strategies.” These findings suggest a strong link between leadership development and enhanced maritime human capital.

Despite strong global and national emphasis on leadership training, significant research gaps persist in understanding its impact on maritime human capital in Indonesia. Wahyudi et al. (2022) noted that “studies on Indonesian seafarer education rarely focus explicitly on leadership outcomes.” Bloor et al. (2020) highlighted that “most maritime HR research still prioritizes technical skill development over leadership.” Chinomona and Sandada (2022) further stated the need for “empirical studies that examine leadership as a distinct construct in human capital development.” Parola et al. (2023) called for “research contextualized in emerging economies with growing maritime sectors,” emphasizing the need for locally grounded evidence. Thus, this study addresses these gaps by examining nautical leadership training and its influence on human capital within Indonesia’s maritime education systems.

This study offers both theoretical and practical contributions to maritime human resource development literature. Sekaran and Bougie (2022) argued that “sector-specific research enhances the relevance and applicability of human capital theories.” The World Bank (2023) noted that “human capital development in transport sectors is critical for sustainable economic growth.” Parola et al. (2023) emphasized that “effective leadership programs increase organizational resilience and adaptability,” supporting strategic workforce development. The IMO (2021) also stated that “leadership training is essential to achieving the goals of sustainable shipping.” Accordingly, this study provides actionable guidance for policymakers, maritime academies, and industry leaders to strengthen Indonesia's maritime human capital through leadership centered curricula and targeted training initiatives.

This study contributes to the maritime human capital literature by developing and empirically testing a structural model that explains the relationships among nautical leadership, motivation, and human capital within the context of Indonesian maritime education using the PLS-SEM approach. Unlike previous studies that primarily focused on technical competencies, this study demonstrates that nautical leadership enhances human capital both directly and indirectly through motivation. These findings enrich the literature on maritime human resource development and provide empirical evidence from a developing maritime nation.

2. Literature Review

2.1 Maritime Human Capital in the Shipping Industry

Human capital is a major strategic asset in the shipping industry that relies heavily on the competence, skills, and readiness of human resources. Becker (1993) defines human capital as the accumulation of knowledge, skills, and abilities acquired through education, training, and work experience. In the maritime context, the quality of human capital determines the level of safety, operational efficiency, and competitiveness of the shipping industry as a whole (Stopford, 2020).

The OECD (2021) emphasizes that human capital in the transportation sector includes technical dimensions, adaptive skills, problem-solving, and long-term career development potential. The study of Parola et al. (2023) shows that strengthening human capital in the maritime sector directly contributes to organizational resilience and adaptability to global technological and regulatory changes. Thus, the development of seafarers' human capital cannot be separated from a comprehensive and sustainable education and training system.

2.2 Concepts and Dimensions of Nautical Leadership

Nautical leadership refers to the ability of ship officers to lead navigation operations, manage crews, make decisions under pressure, and communicate effectively in normal and emergency situations. The International Maritime Organization (IMO) through Model Course 1.39 and the STCW Convention (1978, last amendment) affirms that leadership and teamwork are mandatory competencies for ship officers (IMO, 2021).

Theotokas and Progoulaki (2021) state that onboard leadership has unique characteristics because it takes place in a high-risk, multicultural, and isolated work environment. Lee and Choi (2021) found that nautical leadership training significantly improved the quality of decision-making and safety preparedness. The key dimensions of nautical leadership include decision-making, team management, crisis communication, navigation leadership, and conflict resolution, which directly affect the ship's operational performance.

2.3 Motivation as a Psychological Factor in Seafarer Education and Profession

Motivation is a key psychological factor that affects an individual's willingness to learn, achieve, and develop competencies. Ryan and Deci (2020) through Self-Determination Theory explain that motivation consists of intrinsic and extrinsic motivations, both of which play a role in the formation of professional competencies and career growth. Ryan and Deci (2020) proposed Self-Determination Theory (SDT), which explains that human motivation is driven by the satisfaction of three basic psychological needs: autonomy, competence, and relatedness. In maritime education, leadership practices that support these needs are expected to enhance learning motivation, professional engagement, and competency development, thereby strengthening maritime human capital.

In the maritime context, motivation greatly determines the success of seafarers in mastering complex technical and non-technical skills. Goleman et al. (2020) emphasize that effective leadership is able to create a work environment that supports the psychological needs of individuals, thereby increasing motivation and work engagement. Research by Widyaningrum et al. (2022) also shows that low motivation to learn often correlates with weak leadership readiness and competence of shipping education graduates in Indonesia.

2.4 Nautical Leadership and Motivation Relationship

The literature shows a strong link between leadership and motivation. Supportive, clear, and individual development-oriented leadership has been shown to increase intrinsic motivation and commitment to organizational goals (Ryan & Deci, 2020). In the shipping sector, Lee and Choi (2021) found that effective nautical leadership increases crew confidence, sense of responsibility, and work engagement.

Chia et al. (2022) affirm that transformational leadership styles in maritime environments contribute positively to crew motivation and performance. Therefore, nautical leadership not only functions as an operational control mechanism, but also as a psychological driver that shapes the professional attitudes and behaviors of seafarers.

2.5 The Influence of Nautical Leadership on Human Capital

Various studies confirm that leadership has a direct role in the development of human capital. Stopford (2020) states that leadership quality determines the extent to which technical skills and knowledge can be applied effectively in maritime operations. Bhattacharya (2022) also emphasized that investment in leadership is an integral part of a sustainable human capital development strategy.

In the context of seafarer education, Wahyudi et al. (2022) show that practical leadership training improves job readiness and operational competence of graduates. This indicates that nautical leadership contributes directly to the improvement of technical skills, adaptability, and problem-solving which are at the core of maritime human capital.

2.6 *The Role of Motivational Mediation in Leadership and Human Capital Relationships*

Motivation plays a role as a mediation mechanism that strengthens the influence of leadership on human capital development. Becker (1993) explains that motivated individuals tend to invest more in learning and self-development. Ryan and Deci (2020) added that strong motivation encourages sustainability of competency mastery and professional growth.

Research by Parola et al. (2023) indicates that effective leadership increases human capital not only directly, but also through increased motivation and work engagement. However, empirical studies that specifically examine the role of motivational mediation in the context of Indonesian seafarers' education are still very limited, so more focused and contextual research is needed.

2.7 *Research Gap and Research Position*

Although the global literature has emphasized the importance of leadership and motivation in human capital development, empirical research in Indonesia's maritime context is still relatively minimal. Wahyudi et al. (2022) and Widyaningrum et al. (2022) note that most studies of maritime education in Indonesia still focus on technical aspects, with limited attention to leadership and psychological factors.

In addition, the causal relationship between nautical leadership, motivation, and human capital is rarely tested simultaneously using a SEM-PLS-based quantitative approach. Therefore, this study fills this gap by presenting empirical evidence on the role of nautical leadership and motivation in the development of Indonesian seafarers' human capital, as well as enriching the literature on maritime human resource development in developing countries.

3. Method

This study employed a quantitative, explanatory approach to examine the causal relationships among nautical leadership, motivation, and maritime human capital. A quantitative design is appropriate when the purpose is to "test objective theories by examining the relationships among variables" (Creswell & Creswell, 2021). The explanatory orientation is aligned with the study's aim to clarify the mechanism through which leadership influences human capital, both directly and indirectly through motivation. To achieve this, Structural Equation Modeling using Partial Least Squares (SEM-PLS) was chosen because it is suitable for predictive modeling and complex theoretical structures. Hair et al. (2019) emphasized that "PLS-SEM is particularly valuable for studies seeking prediction and theory development, especially when the model contains multiple indicators." SmartPLS 4.0 was used as the main analytical tool.

The population of this research consisted of Seafarers and STCW trainees enrolled in major Indonesian maritime institutions, STIP Jakarta. These institutions represent the core centers for seafarer education in Indonesia, and their Seafarers undergo standardized leadership and operational training. A purposive sampling technique was applied, targeting respondents who had completed or were currently participating in nautical leadership modules. Etikan et al. (2016) noted that "purposive sampling is effective when the researcher intends to select participants who possess specific characteristics relevant to the study." Regarding sample size, PLS-SEM requires a minimum of 10 times the largest number of indicators measuring a single construct. However, Hair et al. (2019) recommend "a minimum of 200–350 cases for robust PLS-SEM analysis," ensuring stable parameter estimation. Therefore, this study aimed to collect at least 350 valid responses.

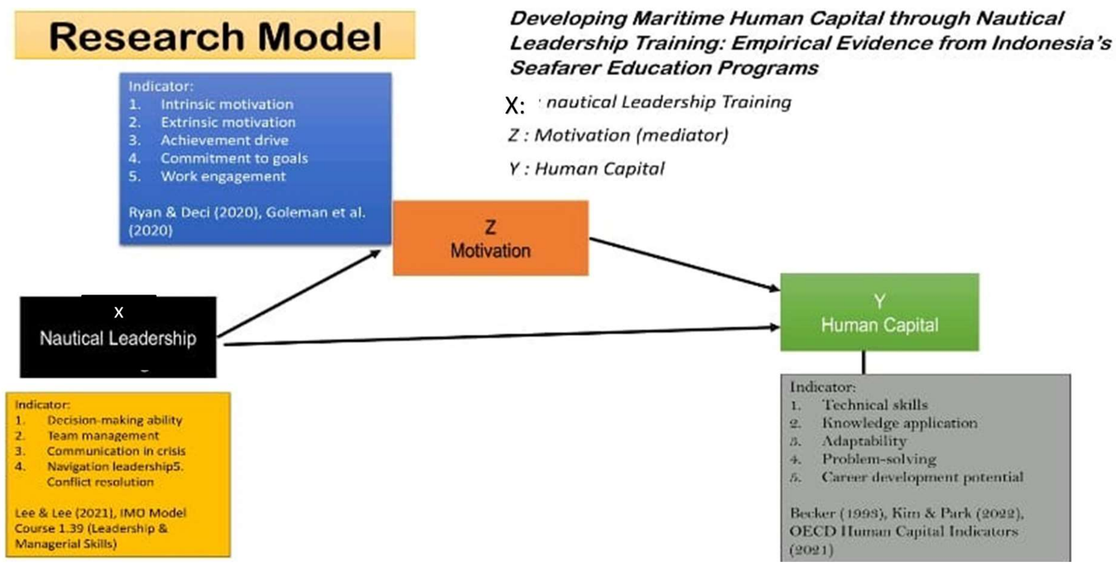

Figure 1. Research Model

Three latent variables were measured: nautical leadership (X), motivation (Z), and human capital (Y). Nautical leadership was operationalized using five indicators covering decision-making ability, team management, crisis communication, navigation leadership, and conflict resolution. These dimensions were aligned with IMO Model Course 1.39 and supported by Lee and Choi's (2021) finding that "leadership competencies play a crucial role in maritime decision-making and situational awareness." Motivation was measured using five indicators adapted from self-determination theory, capturing intrinsic and extrinsic motivation, achievement drive, commitment to goals, and engagement. Ryan and Deci (2020) emphasized that "motivation is a primary predictor of sustained competence development and professional growth." Human capital was measured through five indicators: technical skills, knowledge application, adaptability, problem-solving capability, and career development potential, consistent with OECD (2021) frameworks for workforce competence.

A structured questionnaire was developed using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Likert scales are widely used for measuring perceptions due to their "simplicity, reliability, and ability to capture attitudinal variation" (Joshi et al., 2015). Content validity was ensured through expert review, involving three maritime education specialists and two psychometric experts who assessed clarity, relevance, and construct alignment. A pilot test involving 30 Seafarers was conducted to refine wording and assess initial reliability. As suggested by DeVellis

(2017), pilot testing helps identify ambiguous items and ensures that "each indicator measures the construct it is intended to represent." Items demonstrating poor reliability or low item-total correlations were revised before full deployment.

Data were collected through both online and offline methods to accommodate Seafarers undergoing on-campus academic programs and on-board sea training. Online surveys were distributed through institutional learning management systems and official communication channels, while offline data collection was conducted using printed questionnaires during Seafarers briefing sessions. Groves et al. (2020) noted that "mixed-mode data collection increases response rates and reduces coverage error, particularly in geographically dispersed populations." Participation was voluntary, and anonymity was ensured to minimize response bias. Respondents were briefed about the study's purpose, and informed consent was obtained in accordance with ethical research practices.

Data analysis was conducted using PLS-SEM in SmartPLS 4.0, following a two-step approach involving the measurement model and structural model evaluation. For the measurement model, reliability and validity were assessed through Cronbach's Alpha, Composite Reliability (CR), and Average Variance Extracted (AVE). Henseler et al. (2015) stated that "HTMT is the most accurate method for assessing discriminant validity in variance-based SEM." Items with loadings below 0.70 were considered for removal unless strong theoretical justification existed. Convergent validity was confirmed when AVE exceeded 0.50, and CR values above 0.70 indicated acceptable reliability. The model was iteratively refined to meet PLS-SEM quality criteria.

Table 1. Hypothesis

Hypothesis	Path	Rationale (1–2 lines)	Expected sign
H1	Nautical Leadership → Motivation	Leadership training enhances intrinsic/extrinsic motivation, engagement, and goal commitment among Seafarers (Lee & Choi, 2021; Ryan & Deci, 2020).	+
H2	Nautical Leadership → Human Capital	Leadership skills (decision-making, crisis communication) directly improve technical application, adaptability, and problem-solving — core components of human capital (Stopford, 2020; Lee & Choi, 2021).	+
H3	Motivation → Human Capital	Highly motivated learners invest more in acquiring and applying skills, increasing technical competence and career potential (Ryan & Deci, 2020; OECD, 2021).	+
H4	Nautical Leadership → Motivation → Human Capital (mediation)	Leadership increases motivation, which in turn boosts human capital; motivation partially/fully mediates the leadership → human capital effect (theory & prior empirical suggestions).	**Indirect +**

The structural model evaluation examined path coefficients, effect sizes (f^2), coefficient of determination (R^2), and predictive relevance (Q^2). Chin (1998) highlighted that "path coefficients indicate the strength and significance of hypothesized relationships in SEM." R^2 values of 0.25, 0.50, and 0.75 represent weak, moderate, and substantial explanatory power, respectively. Predictive relevance was tested using the blindfolding procedure, where Q^2 values greater than zero indicate satisfactory predictive ability. Hypothesis testing was conducted using bootstrapping with 5,000 resamples. As recommended by Hair et al. (2019), "bootstrapping provides robust estimates of standard errors and confidence intervals in PLS-SEM." Mediation analysis followed Preacher and Hayes' (2008) approach, allowing an examination of motivation's mediating role between nautical leadership and human capital.

The respondents in this study amounted to 350 seafarers who participated in STCW-based education and training programs at STIP Jakarta. All respondents were selected because they had backgrounds from various regions and at the previous level graduated from various educational institutions, had also attended or were taking nautical leadership training courses so that they were considered to have relevant experience to evaluate the variables of nautical leadership, motivation, and human capital. Respondent characteristics were presented based on gender, age, sailing experience, and educational program to provide an overview of the profile of the research sample.

The purposive sampling technique was chosen because this study requires respondents who have direct experience of nautical leadership training according to STCW standards. Therefore, only cadets or sailors who have taken leadership courses or training are made respondents so that the answers given are in accordance with the purpose of the research. To minimize the potential for common method bias, this study applies several procedures, namely ensuring the anonymity of respondents, explaining that there are no right or wrong answers, and systematically arranging the order of questionnaire items to reduce the tendency of respondents to give uniform answers.

4. Results and Discussion

The evaluation of the measurement model showed that all indicators in the three constructs of Nautical Leadership, Motivation, and Human Capital met the criteria of validity and reliability.

Table 2. Operational Definition of Variables

Variable	Indicators	References
Nautical Leadership	Decision Making, Team Management, Crisis Communication, Navigation Leadership, Conflict Resolution	IMO (2021); Lee & Choi (2021)
Motivation	Intrinsic Motivation, Extrinsic Motivation, Achievement Drive, Goal Commitment, Work Engagement	Ryan & Deci (2020)
Human Capital	Technical Skills, Knowledge Application, Adaptability, Problem Solving, Career Development	OECD (2021); Becker (1993)

The value of outer loadings for the Nautical Leadership construct is in the range of 0.811–0.940, which indicates that indicators such as decision-making, team management, and communication in crisis have a significant contribution in shaping the nautical leadership construct. In the Motivation construct, the loadings value ranges from 0.615–0.960, illustrating that key indicator such as intrinsic motivation, achievement drive, and commitment to goals function well in measuring constructs.

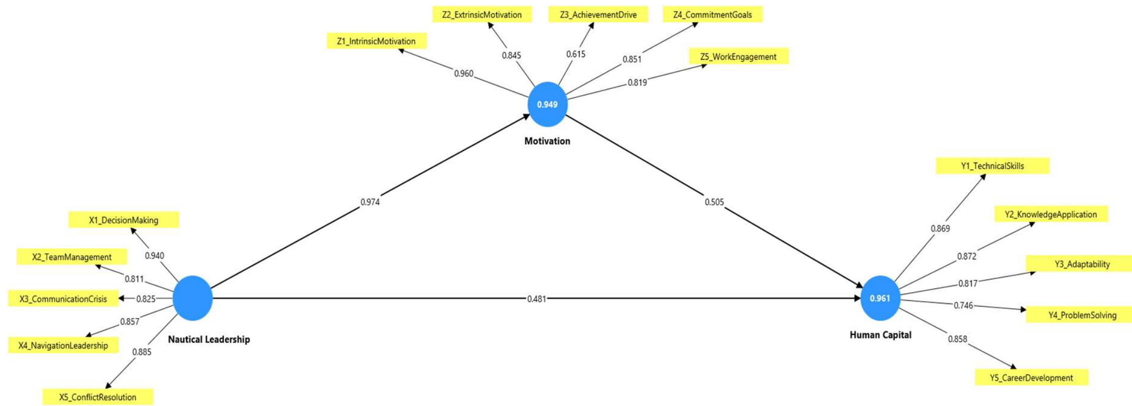

Figure 2. The SEM Result analysis

Meanwhile, the Human Capital indicator gained loadings between 0.746–0.872, indicating strong empirical support for the construct. The Composite Reliability (CR) value for the entire construct is above 0.90, indicating a very high internal consistency. The Average Variance Extracted (AVE) also exceeds 0.50, which confirms convergent validity. With these results, the entire construct is eligible to proceed to the structural model analysis using SEM-PLS.

Tabel 3. Outer Loadings (Convergent Validity)

Construct	Indicator	Loading
Nautical Leadership	X1_DecisionMaking	0.940
	X2_TeamManagement	0.811
	X3_CommunicationCrisis	0.825
	X4_NavigationLeadership	0.857
	X5_ConflictResolution	0.885
Motivation	Z1_IntrinsicMotivation	0.960
	Z2_ExtrinsicMotivation	0.845
	Z3_AchievementDrive	0.615
	Z4_CommitmentGoals	0.851
	Z5_WorkEngagement	0.819
Human Capital	Y1_TechnicalSkills	0.869
	Y2_KnowledgeApplication	0.872
	Y3_Adaptability	0.817
	Y4_ProblemSolving	0.746
	Y5_CareerDevelopment	0.858

The test results show that most indicators have an outer loading value above 0.70. One indicator, namely the Achievement Drive (Z3), has a loading value of 0.615. Although slightly below the ideal value of 0.70, the indicator is still above the minimum acceptable limit for PLS-SEM-based exploratory research (>0.60) and has a strong theoretical basis based on Self-Determination Theory, so the indicator is still maintained in the research model. To ensure that the research data is not influenced by method bias derived from the use of a single instrument, testing is carried out using Harman's Single Factor Test. The results of the analysis showed that the first single factor explained less than 50% of the total variation, so it can be concluded that common method bias was not a significant problem in this study.

Table 4. Reliability and Convergent Validity

Construct	Cronbach's Alpha	Composite Reliability	AVE
Nautical Leadership	0.914	0.938	0.752
Motivation	0.903	0.933	0.736
Human Capital	0.921	0.944	0.773

From the description in table 4 above, it is concluded that all CA and CR values are far >0.70, and AVE >0.50, indicating excellent reliability and strong construct validity.

Table 5. Heterotrait-Monotrait Ratio (HTMT)

Constructs	Nautical Leadership	Motivation	Human Capital
Nautical Leadership	-		
Motivation	0.842	-	
Human Capital	0.781	0.864	-

In addition to testing convergent validity, this study also evaluated discriminant validity using the Heterotrait-Monotrait Ratio (HTMT) value. All HTMT values are below the maximum limit of 0.90, indicating that each construct has a good degree of discrimination and is able to adequately measure different concepts.

Table 6. Path Coefficients (Direct Effects)

Correlation	Line Coefficient (β)	Information
Nautical Leadership → Motivation	**0.974**	Very powerful, significant
Motivation → Human Capital	**0.505**	Moderate–strong, significant
Nautical Leadership → Human Capital	**0.481**	Significant direct influence

Tabel 7. Hypothesis Testing

Hypothesis	Path	β	p-value	Result
H1	Nautical Leadership → Motivation	0.974	<0.001	Supported
H2	Nautical Leadership → Human Capital	0.481	<0.001	Supported
H3	Motivation → Human Capital	0.505	<0.001	Supported

Based on the table of 6 Path Coefficients, it shows that all three relationships are significant. The results show that nautical leadership is the dominant predictor, both of motivation and human capital. The results of the structural model test showed a strong and significant relationship between variables. The influence of Nautical Leadership on Motivation showed a very high path coefficient ($\beta = 0.974$). These results indicate that the better a Seafarers' nautical leadership especially in the aspects of team management, navigation, and crisis communication the higher their intrinsic and extrinsic motivation in carrying out their duties.

The effect of Motivation on Human Capital was also proven to be significant with a coefficient of $\beta = 0.505$, indicating that motivation plays a decisive role in shaping technical skills, adaptability, problem-solving, and career development potential. In addition, Nautical Leadership has a direct influence on Human Capital with a value of $\beta = 0.481$, which means that leadership competencies at the nautical level directly increase the human capital of Seafarers, although some of them are also strengthened by motivation.

Table 8. Mediation Analysis

Relationship	Direct Effect	Indirect Effect	Total Effect	VAF (%)	Mediation
Nautical Leadership → Motivation → Human Capital	0.481	0.492	0.973	50.56	Partial Mediation

Since both direct and indirect effects are significant, motivation partially mediates the relationship between nautical leadership and human capital.

Table 9. R^2 and Q^2

Construct	R^2	Interpretasi	Q^2	Interpretasi
Motivation	**0.949**	Substantial	0.711	Good predictive relevance
Human Capital	**0.961**	Substantial	0.733	Good predictive relevance

The model has very high predictive power, according to the substantial category according to Hair et al. (2019). The R^2 value for Motivation is 0.949, which means that 94.9% of the variance in motivation is influenced by nautical leadership. Meanwhile, Human Capital has an R^2 of 0.961, indicating that the model used has very high predictive power.

Tabel 10. Effect Size (f^2)

Influence	f^2	Category
Nautical Leadership → Motivation	**1.888**	Very large
Motivation → Human Capital	**0.349**	Medium–large
Nautical Leadership → Human Capital	**0.274**	Keep

The influence of nautical leadership on motivation has an extraordinarily large effect size, confirming the importance of leadership training in the maritime context.

Tabel 10. Mediation Summary

Mediation Pathway	Direct Effect	Indirect Effect	Total Effect	Types of Mediation
Nautical Leadership → Motivation → Human Capital	0.481	**0.492**	0.973	**Partial Mediation**

The indirect effect (0.492) was slightly greater than the direct effect (0.481), suggesting that motivation strengthened leadership influence, but direct influence remained significant → partial mediation. Mediation effect testing showed that Motivation acts as a partial mediator in the relationship between Nautical Leadership and Human Capital. Mathematically, the indirect effect ($0.974 \times 0.505 \approx 0.492$) had almost as strong a contribution as the direct effect (0.481). Thus, although nautical leadership directly shapes human capital, motivation still plays a reinforcing role that magnifies that impact.

The conclusion in some points : The SEM model shows very strong validity and reliability, Nautical Leadership is the main predictor that explains 94.9% of motivational variances, Human Capital was strongly influenced by a combination of leadership and motivation ($R^2 = 0.961$), The mediation that occurs is partial mediation, Theoretically, these results are consistent with Ryan & Deci (2020), Becker (1993), IMO Model Course 1.39, and Lee & Choi's (2021) research.

The very high value of the coefficient of determination (R^2) indicates that the research model has an excellent ability to explain variations in motivation and human capital. These conditions indicate that the nautical leadership construct has a very strong relationship with the variables studied. However, these results also need to be interpreted carefully because the study was conducted on one educational institution with relatively homogeneous respondent characteristics.

These results are in line with the theory of Goleman et al. (2020) which emphasizes that motivation is an important psychological component that supports leadership effectiveness. This means that when a Seafarers or officer feels a strong intrinsic motivation, they are more likely to develop professional skills and adaptability in a dynamic maritime work environment.

5. Discussion

The finding that Nautical Leadership has a very strong influence on motivation supports leadership theory in the maritime context presented by IMO Model Course 1.39. Leadership competencies such as the ability to decide under pressure, manage multinational teams, and communicate in crisis situations directly increase Seafarers' self-confidence and motivation. Ryan & Deci (2020) also explain that a supportive leadership environment encourages more stable intrinsic motivation. These findings are consistent with Self-Determination Theory proposed by Ryan and Deci (2020), which suggests that leadership practices supporting autonomy, competence, and interpersonal relatedness strengthen intrinsic motivation. In the maritime context, such conditions encourage continuous competency development and enhance the quality of human capital.

Motivation has proven to be a crucial factor in human capital development. These findings reinforce Becker's (1993) theory of Human Capital, that an individual's investment in learning and developing skills is largely determined by the level of personal motivation. In the context of sailors, high motivation allows Seafarers to more quickly master technical skills, improve adaptability to ship technology, and solve operational problems effectively.

The direct influence of nautical leadership on human capital shows that the role of leadership is not limited to psychological aspects, but also shapes technical and operational competencies. Lee &

Choi (2021) found that nautical leadership training improves the decision-making ability and operational readiness of junior officers, thereby substantively strengthening human capital.

The findings of the mediation resulted in an understanding that motivation amplifies the impact of leadership, but does not replace its direct influence. This suggests that leadership education and training should be designed not only to improve technical skills, but also to foster motivation to achieve, commitment to goals, and work attachment. This is in line with the recommendations of the World Maritime University (2021), which emphasizes the integration of soft-skills and leadership-motivation in the seafarer education curriculum.

The results of the study provide important implications for seafarer education institutions in Indonesia STIP Jakarta. The high R^2 score, the curriculum needs to prioritize strengthening leadership competencies through navigation simulations, team management exercises, and *scenario-based crisis communication*, as well as strengthening career motivation improvement strategies. These findings are in line with the global need for maritime human resources who are adaptive, resilient, and have high leadership competencies in the face of the digitalization and automation of the shipping industry.

6. Conclusion

The findings of this study show that nautical leadership has a very strong role in shaping the motivation and human capital of seafarer Seafarers in Indonesia, with a significant direct influence on both constructs as well as indirect contributions through motivational mediation that are proven to be partial mediators. With very high R^2 values on Motivation (0.949) and Human Capital (0.961), this model confirms that leadership competencies including decision-making, team management, crisis communication, navigation leadership, and conflict resolution are the main foundations for improving technical skills, adaptability, and career development potential. Overall, this study confirms that maritime human capital strengthening strategies cannot be separated from structured leadership training and the development of intrinsic and extrinsic motivation.

This study confirms that nautical leadership plays a significant role in enhancing both motivation and human capital among Indonesian seafarers. Leadership competencies including decision-making, team management, crisis communication, navigation leadership, and conflict resolution not only directly improve technical competence, adaptability, and career development, but also indirectly strengthen human capital through motivation as a partial mediating variable. These findings emphasize the importance of integrating leadership development and motivational strategies into maritime education to strengthen the quality of maritime human capital.

From a practical perspective, the findings provide valuable implications for maritime education institutions and policymakers. Leadership education should extend beyond technical competency development by incorporating communication skills, decision-making, team management, and motivation enhancement into maritime curricula and training programs. Such integration is expected to produce graduates who are better prepared to meet the demands of the global maritime industry.

This study is limited to respondents from STIP Jakarta and employs a cross-sectional research design, which may limit the generalizability of the findings and the ability to capture changes over time. Furthermore, the study focuses only on nautical leadership and motivation, while other factors that may influence maritime human capital were not examined.

Future research is encouraged to involve multiple maritime education institutions across Indonesia, adopt longitudinal research designs, and incorporate additional variables such as emotional intelligence, organizational support, digital competence, and work engagement to develop a more comprehensive model of maritime human capital development.

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XR-Enhanced Maritime English Training for Digital Navigation

Iryna Shvetsova[1]*

[1]Kherson State Maritime Academy, Ukraine

* Corresponding author: isvecova581@gmail.com

Abstract. This study examines the integration of Extended Reality (XR) – including virtual, augmented, and mixed reality – together with AI-enhanced feedback tools into Maritime English training to address the communicative challenges of digital navigation. As bridge operations increasingly rely on automated systems, multimodal interfaces, and hybrid human–machine collaboration, officers must demonstrate precise linguistic performance, situational awareness, and stress-resilient communication. The study proposes an XR-enhanced, competence-oriented instructional model designed to strengthen cadets' procedural fluency, clarity of information exchange, and readiness for safety-critical communication. The methodology combined immersive scenario-based learning with real-time speech-recognition feedback and adaptive AI-generated micro-tasks aligned with IMO SMCP requirements. Empirical observations and system-generated performance indicators show that XR environments improve terminological accuracy, interactional fluency, and responsiveness during emergency scenarios and team-coordination tasks. Learners additionally reported increased confidence and reduced hesitation when communicating under operational pressure. The findings demonstrate that XR-enhanced Maritime English instruction offers a scalable and pedagogically effective approach that supports digital transformation in maritime education, reinforces safety-oriented communication practices, and prepares cadets for the linguistic and multimodal demands of next-generation navigation systems.

Keywords. Maritime English; Extended Reality (XR); immersive learning; AI-enhanced training; digital navigation.

1. Introduction

The accelerating digitalization of maritime transport has reshaped navigational operations and the role of seafarers in decision-making processes. Modern vessels increasingly rely on integrated digital technologies, advanced sensor systems, and varying levels of automation, requiring officers to monitor complex information environments and interact effectively with automated systems. The emergence of maritime autonomous and highly automated systems introduces new challenges related to risk governance, situational awareness, and human oversight, highlighting the need for professionals who can interpret system-generated information and make informed operational decisions in technologically advanced maritime contexts (Goerlandt, 2020). Digital navigation environments can be conceptualized as multilayered communication systems integrating technological, procedural, human–machine, and interactional dimensions. In such environments, officers continuously synthesize multimodal operational inputs while maintaining safe and effective communication performance. The structure of these interactions is illustrated in Figure 1. Consequently, Maritime English must be reconsidered not only as a linguistic discipline but as an operational competence essential for safe bridge performance.

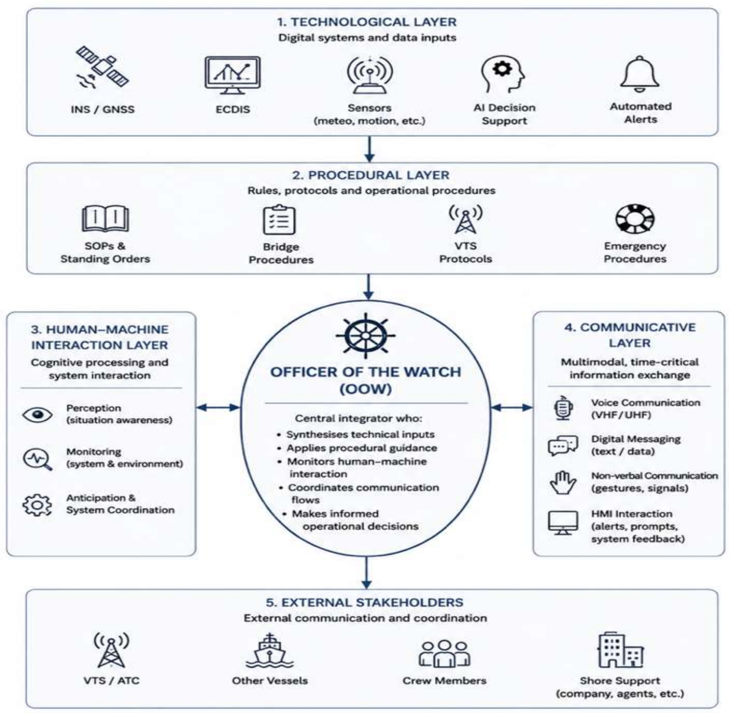

Figure 1. Multilayered Communication Structure of Digital Navigation Environments
Source: developed by the author.

Although Maritime English is included in the competency requirements of the STCW Convention and Code (International Maritime Organization, 2017), traditional classroom instruction cannot fully replicate the complexity, time pressure, and multimodal communication demands of contemporary bridge operations. Modern maritime environments require officers not only to use standardized maritime language effectively but also to interpret information from multiple technological systems, maintain situational awareness, and support operational decision-making. As maritime operations become increasingly digitalized and automated, there is a growing need for training approaches that integrate linguistic competence with operational and technological skills (Goerlandt, 2020). XR-based learning environments offer opportunities to address this need by providing realistic scenarios that combine communication, decision-making, and human–system interaction in authentic maritime contexts.

Extended Reality (XR), encompassing virtual, augmented and mixed reality technologies, provides immersive and context-rich learning environments that support authentic interaction and experiential learning. Research in higher education has demonstrated that immersive environments can enhance learner engagement, knowledge retention, and skill transfer more effectively than conventional instructional approaches (Radianti et al., 2020). Given that Maritime English is closely integrated with operational communication and decision-making, XR is particularly well suited to supporting its development.

Within the maritime domain, immersive simulation technologies have demonstrated considerable potential for professional training and operational preparedness. Research indicates that virtual and mixed reality environments enable learners to practise complex and potentially hazardous procedures in realistic yet controlled settings, thereby enhancing experiential learning and skill development (Dewan et al., 2023). Furthermore, immersive environments provide opportunities for repeated practice, immediate feedback, and scenario-based learning that support both operational and communicative competence (Radianti et al., 2020; Dewan et al., 2023). Given the increasing digitalization of maritime operations, XR-based training represents a promising instructional approach for preparing students to meet the communicative and operational demands of modern bridge environments.

Building on these insights, the present study investigates the integration of XR and AI-enhanced feedback into Maritime English training at Kherson State Maritime Academy. It introduces a competence-oriented instructional model aligned with realistic digital navigation tasks and evaluates its impact on linguistic accuracy, communicative fluency, situational awareness and stress-resilient decision-making. The study contributes to ongoing discussions on the digital transformation of maritime education and its significance for safety-critical communication.

2. Research Method

This study employed a mixed-methods design to capture both linguistic and operational dimensions of students' performance in XR-enhanced Maritime English training. The methodological approach was informed by Ericsson's (2008) concept of deliberate practice, which emphasizes the role of repeated practice, immediate feedback, and progressive task refinement in the development of professional expertise. Accordingly, the training design incorporated iterative practice cycles supported by digital feedback mechanisms and performance monitoring tools, enabling students to refine their communicative and operational skills through repeated engagement with authentic maritime scenarios.

2.1 Participants and Training Context

The study involved 42 second- and third-year navigation cadets from Kherson State Maritime Academy who possessed prior knowledge of Maritime English but had no previous experience with XR-supported learning environments. The XR-enhanced training cycle lasted eight weeks and was integrated into the regular Maritime English curriculum. Cadets participated in two XR-supported sessions per week combining immersive communication scenarios, AI-assisted speech analysis, and instructor-led reflective debriefing activities. This integration ensured ecological validity and complemented conventional MET components such as classroom instruction and simulator-based navigation training.

2.2 XR Learning Environment and AI Feedback

The XR training environment combined VR, AR, and MR modalities to replicate key communicative situations on the bridge. Commercially available VR headsets, AR-supported visualization tools, and AI-enhanced speech-recognition software were integrated into immersive maritime communication scenarios. The training tasks were implemented through scenario-based simulations reproducing bridge communication, emergency coordination, and human-system interaction conditions. VR simulations recreated operational scenarios, AR overlays supported terminology acquisition, and MR tasks enabled interaction with virtual crew members and system prompts. This multimodal configuration ensured cognitive and spatial realism while embedding linguistic activity within authentic operational contexts (Dewan et al., 2023; Radianti et al., 2020). AI tools monitored pronunciation, lexical use, and recurring error patterns, providing immediate individualized feedback and enabling repeated practice cycles. In line with the principles of deliberate practice, the feedback mechanisms supported continuous performance refinement and progressive skill development (Ericsson, 2008).

2.3 Data Collection and Analysis

Four data sources were used: observational notes, system-generated performance metrics, instructor evaluations aligned with STCW requirements (International Maritime Organization, 2017), and learner self-assessments. Qualitative data were thematically analysed, while quantitative indicators were examined using descriptive statistics. Integrating these analytical layers enabled a comprehensive assessment of how immersive learning environments and AI-enhanced feedback mechanisms shaped students' communicative development and operational readiness. Overall, the methodological design ensured robust triangulation and provided a multi-dimensional perspective on the impact of XR-supported training on Maritime English competence.

3. XR-Based Maritime English Instruction Model

The instructional model proposed in this study presents an integrative, competence-oriented framework that embeds Extended Reality (XR) technologies into the pedagogy of Maritime English. The model is intended to address the evolving communicative demands of contemporary digital navigation and to support cadets in developing operationally relevant linguistic, interactional, and cognitive competencies. More broadly, it responds to the need for innovative instructional strategies that extend beyond traditional classroom formats and reflect the increasing technological sophistication of maritime workplaces.

3.1 Conceptual and Pedagogical Foundations

The design of the model is grounded in several theoretical constructs central to applied linguistics and maritime training. First, the model draws on situated learning theory, emphasizing authentic operational learning contexts. XR environments, because of their immersive and interactive nature, create conditions under which linguistic meaning-making becomes inseparable from operational action. Second, the model reflects principles of **competence-based education**, emphasizing measurable outcomes such as communicative clarity, procedural fluency, and pragmatic appropriateness. Maritime communication is inherently multimodal and dynamic; therefore, competence must be developed not only at the linguistic level but also at the levels of situational awareness, decision-making, and coordination. Third, the model incorporates insights from **digital literacy and human–technology interaction research**, recognizing that future officers must navigate hybrid communicative spaces that include human interlocutors, automated systems, digital displays, and sensor-derived alerts. Consequently, language instruction must prepare learners to interpret, respond to, and integrate digital information streams while maintaining communicative precision. Collectively, these foundations position XR as a transformative pedagogical environment for maritime communication training.

3.2 Modular Structure of XR-Enhanced Maritime English Training

To operationalize these theoretical principles, the model is organized into a set of interrelated modules that correspond to the learning objectives of Maritime English curricula. Each module is supported by tailored XR scenarios designed to stimulate authentic interaction, promote critical thinking, and reinforce experiential learning.

Module 1: Maritime Vocabulary and Terminology Acquisition. AR-based overlays project terminology onto navigational objects, instruments, and operational interfaces, supporting contextualized lexical retention and terminology–function association.

Module 2: Bridge Team Communication. VR simulations replicate team-based bridge environments where cadets practice coordination, clarification strategies, and operational information exchange under cognitively demanding conditions.

Module 3: Emergency and Safety Communication. High-stress XR emergency scenarios develop rapid communication, information prioritization, and the ability to issue and interpret urgent instructions under operational pressure.

Module 4: Communication with Vessel Traffic Services (VTS). MR environments simulate hybrid communication channels involving radio transmissions, digital messaging interfaces, and variable noise conditions, supporting distributed communication management and clarity in technologically mediated interaction.

Module 5: Human-Machine Interaction Communication. Learners interact with virtual interfaces, automated alerts, and system-generated prompts, developing the ability to interpret digital communication cues and respond effectively within hybrid bridge ecosystems. The module organization ensures that XR becomes a flexible pedagogical tool capable of supporting diverse communicative functions, from descriptive and procedural communication to collaborative problem-solving and automated-system dialogue.

The XR-enhanced instructional framework is organized into training modules aligned with communication tasks and STCW-oriented skill development. The framework structure is summarized in Table 1.

Table 1. Modular Structure of XR-Enhanced Maritime English Training

Module	*XR Modality*	*Communicative Focus*	*Typical Tasks*	*AI Support*
Maritime Vocabulary and Terminology Acquisition Foundations	AR	terminology precision and object identification	AR-supported equipment labeling; procedural naming tasks	lexical accuracy monitoring
Bridge Team Communication	VR	teamwork and closed-loop communication	helm orders; situational reporting; bridge coordination	fluency and interaction analysis
Emergency and Safety Communication	VR/MR	high-pressure communication clarity	MOB drills; fire response; mayday scenarios	error detection and timing analysis
VTS and Hybrid Communication	VR + digital interfaces	mixed-channel communication	position reporting; VHF-digital coordination	message coherence analysis
Human–Machine Interaction	MR	interaction with automated systems	alert interpretation; AI-assisted response tasks	adaptive task difficulty and performance analytics

Source: developed by the author based on IMO Model Course 3.17 and XR–MET framework.

3.3 Task Architecture and AI-Supported Scaffolding

The task architecture within the XR-enhanced instructional model follows a hierarchical progression designed to support increasingly complex communicative performance. At the controlled-task level, learners focus on linguistic accuracy through guided VR sequences and AR cues that reinforce key expressions and operational terminology. Communicative tasks expand this foundation by requiring interaction with virtual agents or peers, promoting fluency, negotiation of meaning and coordination in dynamic contexts. Scenario-based tasks represent the highest level of complexity, integrating linguistic, cognitive and operational skills within comprehensive simulations that mirror real bridge conditions and foster transferable competence.

Complementing this task hierarchy, AI-driven scaffolding provides continuous pedagogical support. Speech-recognition tools monitor pronunciation and lexical accuracy, while diagnostic algorithms identify recurrent errors and generate individualized micro-tasks. Adaptive difficulty settings adjust cognitive load in real time, and performance dashboards offer detailed analytics on communicative behaviour, response patterns and task efficiency. Together, these automated mechanisms and immersive environments create a feedback-rich learning system that enables cadets to refine their communicative abilities through iterative, targeted practice.

3.4 Integration into the Instructional Workflow

Finally, the model is designed to integrate seamlessly into broader training workflows. XR sessions are complemented by instructor-led debriefings, reflective discussions, and analytical tasks that help learners interpret their performance and internalize effective communicative strategies. Such integration ensures that the development of Maritime English competence is not confined to isolated training episodes but becomes part of a continuous experiential learning cycle. Overall, the XR-based instructional model provides a comprehensive pedagogical framework that aligns with the operational realities of digital navigation and supports the development of linguistically accurate, context-aware, and safety-oriented communication competence.

4. Results

The implementation of the XR-enhanced instructional model produced clear improvements in cadets' linguistic and operational communication performance. Evidence from observational records, system-generated analytics, instructor evaluations and learner self-assessments consistently indicates positive development across accuracy, fluency, situational awareness and interactional behaviour.

4.1 Linguistic Accuracy and Fluency

Cadets demonstrated higher lexical precision through AR-supported terminology tasks and context-based vocabulary use. Fluency also improved, with longer uninterrupted utterances, fewer hesitations and more effective self-correction during VR and MR communication activities. Real-time AI feedback strengthened pronunciation and prosodic control, contributing to more consistent and natural speech delivery. Comparative performance indicators observed across the training cycle are summarized in Table 2. The normalized indices reflect improvements in linguistic accuracy, fluency, situational awareness, and team coordination following repeated XR-based communication practice.

Table 2. Comparative Performance Indicators Before and After XR-Based Training

Competence Area	*Before Training*	*After Training*
Linguistic Accuracy	0.62	0.86
Fluency	0.57	0.82
Situational Awareness	0.55	0.88
Team Coordination	0.48	0.80

Source: developed by the author based on XR training observations and performance analytics.

As shown in Table 2, the most substantial improvements were observed in situational awareness and communicative fluency, indicating that XR-supported environments effectively integrate operational cognition with language performance.

4.2 Situational Awareness and Decision-Making

Immersive simulations enhanced cadets' ability to integrate visual cues, system alerts, and contextual factors into communicative decisions. Learners became more adept at prioritizing critical information, sequencing messages coherently, and adjusting communication strategies to match scenario complexity, demonstrating the development of multimodal literacy essential for digital navigation.

4.3 Collaborative and Interactional Competence

Team-based XR activities supported clearer coordination, improved turn-taking and more effective clarification practices. In multi-user mixed-reality scenarios, cadets managed distributed communication flows with increasing confidence, responding more accurately to dynamic inputs from virtual crew and automated systems.

4.4 Communication Under Stress

Exposure to emergency and time-critical situations significantly reduced communicative hesitation. Over repeated simulations, cadets produced faster, clearer and more structured messages, showing greater composure during high-pressure interactions. This suggests that immersive stress scenarios foster resilience and strengthen safety-oriented communication habits.

4.5 Learner Perceptions and Confidence

Self-assessment data reflected strong engagement and notable increases in confidence when using domain-specific terminology, interacting in complex operational contexts and managing cognitive load. Learners valued the opportunity to *experience* communicative roles rather than merely study them, while instructors reported that XR revealed performance patterns not observable in traditional classroom settings. Overall, the results demonstrate that combining XR environments with AI-supported feedback provides an effective, multidimensional approach to developing communicative competence for digital navigation and preparing cadets for operationally realistic bridge communication.

5. Discussion

The findings of this study highlight the pedagogical effectiveness and transformative potential of XR-enhanced Maritime English instruction. When interpreted through the lens of contemporary maritime education and training (MET) research, several key themes emerge. These themes relate to shifts in communicative competence demands, the pedagogical value of immersive learning, and the broader implications for the digital transformation of maritime operations.

5.1 Communicative Demands of Digital Navigation

Students' improved performance in integrating visual cues, interpreting automated alerts, and coordinating verbal responses reflects the communicative and operational demands of contemporary digital navigation. Modern bridge operations increasingly require officers to process information from multiple integrated systems while maintaining effective communication and situational awareness.

According to Goerlandt (2020), the transition towards autonomous and highly automated maritime operations places greater emphasis on human oversight, risk-informed decision-making, and interaction with complex technological systems. By replicating these conditions, the XR-based learning environment enabled students to practise interpreting multimodal information and responding appropriately within realistic operational scenarios, thereby strengthening both their communicative competence and their readiness for technology-driven maritime workplaces.

5.2 XR as an Accelerator of Contextualized Language Learning

Across modules, XR technology enabled cadets to encounter language in deeply contextualized settings. This finding resonates with research on experiential and situated learning, which argues that authentic contexts promote stronger retention, higher transferability, and deeper cognitive engagement. The enhanced fluency and reduced hesitation seen in the results demonstrate that cadets benefit from the immersive nature of VR, AR, and MR environments, where language use is integrated into operational tasks rather than detached from them. Furthermore, the integration of stress variables – time pressure, environmental noise, unexpected system changes – contributed to more realistic communicative performance, reflecting conditions cadets are likely to face in real navigation.

5.3 AI-Driven Feedback and Accelerated Skill Development

AI-based speech recognition and automated error detection contributed to significant improvements in pronunciation and lexical accuracy. Immediate and individualized feedback enabled students to identify performance gaps, monitor their progress, and refine their language use more efficiently. These findings align with Ericsson's (2008) concept of deliberate practice, which emphasizes the importance of feedback, repetition, and progressive performance refinement in the development of expertise. The adaptivity of the feedback system further supported iterative learning by enabling students to engage repeatedly with increasingly challenging communicative tasks, thereby accelerating the development of both linguistic and operational competence.

5.4 Stress-Resilient Communication and Emergency Behaviour

One notable outcome was the reduction in communicative hesitation during high-pressure scenarios. Students became more capable of issuing concise reports, coordinating actions, and maintaining effective communication under simulated stress conditions. These findings suggest that immersive training environments can strengthen the integration of linguistic performance and operational decision-making in demanding maritime contexts. The ability of XR technologies to recreate realistic emergency situations in a safe and controlled environment appears particularly valuable for developing communication skills required during critical incidents. Furthermore, as maritime operations become increasingly complex and technology-driven, effective communication depends not only on the use of standardized phraseology but also on the ability to adapt to uncertainty, time pressure, and rapidly changing operational conditions (Goerlandt, 2020; International Maritime Organization, 2017). In this regard, XR environments may contribute to the modernization of SMCP-oriented training by supporting flexible, context-sensitive communication strategies in non-routine situations.

5.5 Enhancement of Collaborative and Multimodal Interaction Competence

Team-based MR simulations reinforced students' skills in coordination, mutual confirmation, and shared situational awareness – core elements of bridge resource management. These findings are consistent with previous research demonstrating that immersive learning environments facilitate collaboration, communication, and experiential learning through realistic, interactive, and multimodal engagement (Dewan et al., 2023; Freina & Ott, 2015; Radianti et al., 2020). By participating in shared virtual scenarios and distributed communication processes, students were required to negotiate meaning, exchange information, and coordinate actions in real time. Such experiences supported the development of teamwork and interactional competence, which remain essential for safe maritime operations but are often insufficiently addressed in traditional Maritime English instruction. Furthermore, the integration of verbal, visual, and contextual cues within XR environments contributed to more authentic communication practices and enhanced collective situational awareness.

5.6 Implications for Maritime Education and Training

The integration of XR into Maritime English instruction offers a scalable and flexible enhancement to conventional Maritime Education and Training (MET) practices. Previous research has demonstrated the value of immersive technologies in providing realistic, repeatable, and experiential learning opportunities that support both operational and communication-related skill development (Dewan et al., 2023; Freina & Ott, 2015; Radianti et al., 2020). The present study further suggests that when combined with AI-enhanced feedback mechanisms, XR extends its educational value beyond operational training to the development of communicative competence.

Finally, the results indicate that XR-supported instruction strengthens safety-oriented communication behaviours through repeated exposure to realistic and potentially risk-prone scenarios. Improvements in students' communicative clarity, information prioritization, and decisiveness are consistent with STCW expectations regarding communication as a safety-critical professional competence (International Maritime Organization, 2017). By integrating language learning with operational practice, XR contributes to the development of a proactive safety culture and prepares future maritime professionals for the communicative demands of technology-rich maritime environments.

5.7 Limitations of the Study

The study has several limitations. First, the participant sample was limited to cadets from a single maritime institution, which may affect the generalizability of the findings. Second, the research focused on short-term performance indicators rather than long-term retention of communicative competence. In addition, the XR scenarios were implemented under controlled instructional conditions and were not fully integrated with full-mission bridge simulators. Future studies should explore long-term performance and multicultural interaction in complex operational environments.

6. Conclusion

This study examined the use of Extended Reality (XR) and AI-supported feedback systems in Maritime English training aimed at meeting the communicative demands of digital navigation. The findings show that immersive, context-rich environments improve cadets' linguistic accuracy, situational awareness, interactional behaviour, and communication performance under stress.

The proposed XR-based instructional model effectively integrates Maritime English learning into realistic operational conditions by combining VR, AR, and MR environments with adaptive AI feedback. As a result, cadets develop communication skills that function not only as linguistic competencies but also as operational tools essential for safe bridge performance.

Empirical evidence demonstrates notable improvements in fluency, confidence, and teamwork, supported by repeated practice in high-pressure scenarios. AI-driven feedback further enhances learning efficiency through immediate, individualized correction.

From an educational perspective, XR-supported instruction offers a scalable and cost-effective enhancement to traditional Maritime English training and aligns well with the digital transformation of maritime operations. Overall, the study confirms XR's potential to strengthen communicative competence and support maritime safety culture. Future research should investigate long-term skill retention, multicultural crew simulations, and integration with full-mission bridge systems.

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A Scenario-Based Robust Optimization Model for Warehouse Planning in Shipbuilding Supply Chains under Ripple Effects

Sis Ozgun Yamak Ormeci1,[1]*, Anna Shotadze[3], Murat Ozkok[2]

[1]Karadeniz Technical University, Graduate School of Natural and Applied Science, Türkiye

[2] Karadeniz Technical University, Surmene Faculty of Marine Sciences, Türkiye

[3] Batumi State Maritime Academy, Georgia

* Corresponding author: sisozgunyamak@ktu.edu.tr

Abstract. Shipbuilding supply chains (SSCs) are characterized by long production horizons and strong interdependencies among material flows. Disruptions affecting critical inputs such as steel plates, profiles, and pipes can rapidly propagate across multiple shipyards and parallel projects, generating ripple-effect-driven instability. Despite the relevance of this phenomenon, quantitative modeling efforts addressing ripple effects in shipbuilding logistics remain limited. This study develops a scenario-based robust optimization framework to support resilient material planning in shipbuilding supply chains under demand uncertainty. The supply network is modeled as a two-echelon structure in which material flows move from suppliers to candidate warehouses and subsequently to shipyards. Demand uncertainty is represented through discrete disruption scenarios reflecting increased material requirements. The proposed formulation focuses on evaluating system performance under adverse conditions by incorporating cost components associated with warehouse activation, material transportation, and unmet demand. The study presents an interpretable robust baseline model that evaluates warehouse activation and material flow decisions under progressively increasing disruption severity and also provides a structural basis for future stochastic extensions. Numerical results indicate that stable network configurations can be maintained as disruption severity increases, while system costs adjust in response to amplified material needs. Overall, the proposed framework provides an initial decision-support basis for analyzing warehouse configuration and material flow planning under ripple-effect conditions in shipbuilding supply chains. The findings show that a stable warehouse configuration can support resilient material planning, while operational flow adjustments absorb increasing demand pressure under ripple-effect conditions.

Keywords: Ripple effect, Shipbuilding supply chain, Robust optimization, Demand uncertainty, Warehouse configuration

1. Introduction

Global supply chains have become increasingly vulnerable to large-scale disruptions triggered by pandemics, geopolitical conflicts, natural disasters, and industrial crises. These disturbances propagate through interconnected supply networks, generating cascading failures in production, transportation, and distribution systems. This phenomenon, known as the ripple effect, amplifies localized disruptions into system-wide instability and has therefore become a central concept in resilience-oriented supply chain design (Dolgui et al., 2018; Hosseini & Ivanov, 2019; Ivanov et al., 2013).

Prior studies have examined ripple-effect propagation using probabilistic models, simulation approaches, and optimization-based decision frameworks, linking disruption dynamics with resilience, viability, and recovery planning. For instance, stochastic–robust optimization has been employed to mitigate cascading disruptions in healthcare and energy supply chains (Fattahi & Govindan, 2018; Yılmaz et al., 2023), while simulation studies have analyzed how epidemic outbreaks, warehouse disruptions, and coordinated routing decisions influence propagation patterns and recovery trajectories (Andoh & Yu, 2023; Ivanov, 2018; Luo et al., 2024). Additional research has explored the role of supplier flexibility, alternative routing, and regional coordination in limiting disruption spread across multi-tier networks (Kamalahmadi & Mellat-Parast, 2016). Despite these advances, the application of ripple-effect modeling to project-based industries remains limited. SSCs pose a unique challenge due to long production cycles and strong interdependencies among supply chain tiers, and reliance on a limited set of critical materials (particularly steel plates, profiles, and pipes) used in hull construction. Disruptions affecting these materials can rapidly propagate across parallel shipbuilding projects, leading to schedule delays, idle capacity, and substantial financial losses. Existing maritime and shipbuilding literature has predominantly focused on probabilistic risks, digital transformation, routing strategies, port-level resilience, and operational disruptions (Centobelli et al., 2023; Ferreira et al., 2018; Niu et al., 2026). Although some studies have modeled disruption propagation through Bayesian networks and stochastic shipment planning (Yazdani & Aouam, 2023; Zhang et al., 2026), he role of intermediate warehouses in buffering ripple effects by stabilizing material flows between suppliers and shipyards has not been explicitly investigated. In the Marmara Region (which hosts Tuzla and Yalova shipyard clusters), the strategic positioning of intermediate depots plays a critical role in sustaining production continuity under disruption-prone conditions. Motivated by this research gap, the present study proposes a scenario-based robust optimization framework for shipbuilding supply chains. The model focuses on the strategic activation of warehouses, and the allocation of material flows from suppliers to shipyards under ripple-effect-driven demand uncertainty. Rather than presenting a fully developed stochastic formulation, this study establishes a robust baseline structure that prioritizes feasibility under adverse demand scenarios. The proposed model minimizes the worst-case total supply chain cost, including warehouse activation costs, transportation costs, and penalty cost associated with unmet demand. By explicitly accounting for multiple demand scenarios, the formulation ensures that the resulting decisions remain viable even when material requirements at shipyards increase due to upstream or regional disruptions. The contribution of this study is threefold. First, it formulates a scenario-based robust optimization model for warehouse planning in shipbuilding supply chains under ripple-effect-driven demand uncertainty. Second, it provides a transparent numerical setting in which the response of warehouse activation, supplier engagement, and material flow decisions can be examined under gradually increasing disruption severity. Third, it offers managerial insight into how stable warehouse configurations can support resilient material planning in shipbuilding clusters where facility decisions are strategic and costly to revise.

2. Material and Method

2.1 Structure of the Shipbuilding Supply Chain Under Disruption Conditions

This study develops a robust optimization model to support strategic warehouse location and material flow decisions within the shipbuilding supply chain under ripple-effect-driven disruption conditions. The model is constructed as a scenario-based robust framework, serving as a preliminary structure for an extended two-stage stochastic formulation, which will be addressed in future work. The overall structure of the supply chain is illustrated in Figure 1 and consists of a two-echelon network in which critical inputs—such as steel plates, profiles, and pipes—are transported from suppliers to warehouses and subsequently distributed to shipyards. Within this network, the set of suppliers S, the set of candidate warehouses W, and the shipyards K constitute the main decision-making entities of the system. Demand at the shipyard level is exposed to significant variability during major disruptions, particularly when disturbances originating at upstream nodes propagate throughout the network. These ripple-effect conditions introduce uncertainty that directly affects material requirements and undermines traditional planning approaches. To capture this dynamic, the proposed model evaluates system performance under multiple demand scenarios, each corresponding to a distinct disruption severity level. In this structure, transportation links between suppliers, warehouses, and shipyards are assumed to be fixed, while demand parameters vary across scenarios to reflect the uncertain operating environment. The primary objective of the model is to minimize the total cost of the supply chain, including warehouse activation costs, transportation costs across both echelons, and penalty costs associated with unmet demand, while ensuring the robustness of decisions across all scenarios. By focusing on worst-case realizations, the model prioritizes solutions that remain feasible and cost-effective even when material requirements escalate unexpectedly due to upstream disruptions. This worst-case perspective enhances the resilience of the supply network and provides decision-makers with strategies that maintain service reliability under severe disruption conditions. To sustain analytical clarity, the model is formulated over a single planning period representing a typical procurement cycle in shipbuilding. Material attributes, capacity limits, costs, and distances are assumed to remain constant during this period. Uncertainty is introduced solely through shipyard demand, capturing the indirect ripple effects of disruptions occurring elsewhere in the regional supply network. Transportation routes between nodes are considered fixed throughout the planning horizon, emphasizing the impact of demand fluctuations rather than structural reconfiguration of the network. The numerical instance is intentionally kept compact to provide a transparent and traceable evaluation of the proposed robust formulation. Rather than representing a full-scale industrial case, it serves as a controlled test environment for observing how warehouse activation, supplier engagement, and material flow decisions respond to increasing disruption severity. This design allows the model behavior to be examined clearly before extending the framework to larger real-world shipbuilding networks.

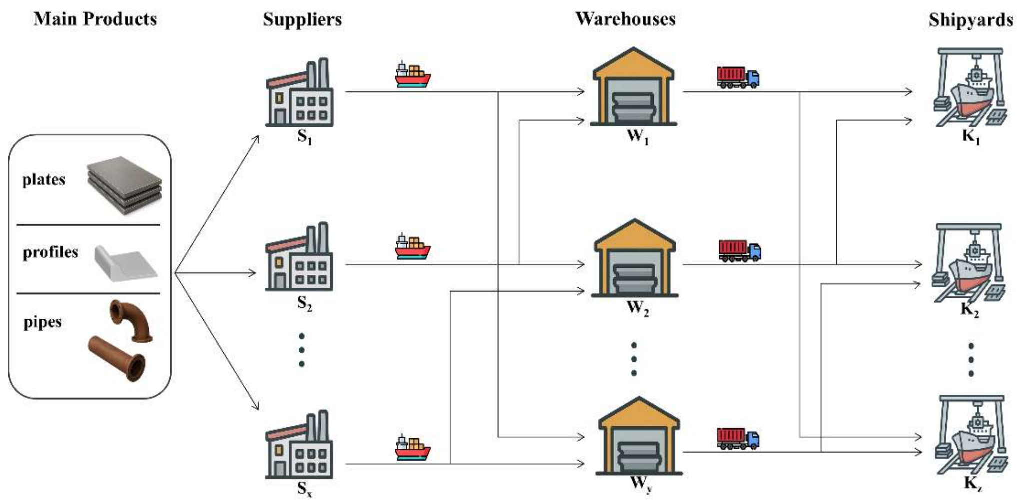

Figure 1. Structure of the proposed shipbuilding supply chain network under disruption conditions

2.2 Mathematical formulation of the robust model

This subsection introduces the notation and the complete mathematical formulation of the scenario-based robust shipbuilding supply chain model developed in this study. The network includes suppliers, candidate warehouses, and shipyards under multiple demand scenarios.

Sets and indices

S: set of suppliers, indexed by s
W: set of possible warehouses, indexed by w
K: set of shipyards, indexed by k
R: set of demand scenarios, indexed by r ($\boldsymbol{R} = \{\boldsymbol{r_1}, \boldsymbol{r_2}\}$)
L: set of uncertainty levels, indexed by l ($\boldsymbol{L} = \{\boldsymbol{0}, \boldsymbol{1}, \dots, \boldsymbol{10}\}$)

Parameters

cap$\boldsymbol{S_s}$*: capacity of supplier s*
cap$\boldsymbol{W_w}$*: capacity of warehouse w*
$\boldsymbol{d_k^0}$*: nominal demand of shipyark k*
$\boldsymbol{d_{kr}(l)}$*: demand of shipyark k in scenario r at uncertainty level l*
$\boldsymbol{f_w}$*: fixed opening cost of warehouse w*
$\boldsymbol{g_k}$*: penalty cost per unit of unmet demand at shipyard k*
$\boldsymbol{c_{sw}}$*: unit transportation cost from supplier s to warehouse w*
$\boldsymbol{c_{wk}}$*: unit transportation cost from warehouse w to shipyard k*
v: upper bound on total cost (budget limit)

Transportation costs are computed from distances and mode-specific unit costs as in the implementation

$\boldsymbol{c_{sw}}$*=costSea.dist*$\boldsymbol{SW_{sw}}$*,* $\boldsymbol{c_{wk}}$*=costRoad.dist*$\boldsymbol{WK_{wk}}$

Decision variables

$\boldsymbol{y_w} \in \{\boldsymbol{0}, \boldsymbol{1}\}$*: equals 1 if warehouse w is opened*
$\boldsymbol{x_{sw}^r} \geq \boldsymbol{0}$*: flow from supplier s to warehouse w under scenario r*
$\boldsymbol{x_{wk}^r} \geq \boldsymbol{0}$*: flow from warehouse w to shipyard k under scenario r*
$\boldsymbol{u_{kr}} \geq \boldsymbol{0}$*: unmet demand atshipyard k in scenario r*
$\boldsymbol{Cost_r} \geq \boldsymbol{0}$*: total cost in scenario r*

Z: worst-case scenario cost

Min-max robust formulation:

$$min_{y,x,u} max_{r\in R}\left\{\sum_{w\in W} f_w y_w + \sum_{s\in S}\sum_{w\in W} c_{sw} x_{sw}^r + \sum_{w\in W}\sum_{k\in K} c_{wk} x_{wk}^r + \sum_{k\in K} g_k u_{kr}\right\} \tag{1}$$

$$Cost_r(y,x,u) \sum_{w\in W} f_w y_w + \sum_{s\in S}\sum_{w\in W} c_{sw} x_{sw}^r + \sum_{w\in W}\sum_{k\in K} c_{wk} x_{wk}^r + \sum_{k\in K} g_k u_{kr}, \forall r \in R \tag{2}$$

Subject to:

$$\sum_{w\in W} x_{sw}^r \le capS_s, \forall s \in S, \forall r \in R \tag{3}$$

$$\sum_{s\in S} x_{sw}^r \le W_w y_w, \forall w \in W, \forall r \in R \tag{4}$$

$$\sum_{s\in S} x_{sw}^r = \sum_{k\in K} x_{wk}^r, \forall w \in W, \forall r \in R \tag{5}$$

$$\sum_{w\in W} (x_{wk}^r + u_{kr}) = d_{kr}(l), \forall k \in K, \forall r \in R \tag{6}$$

$$Cost_r(y,x,u) \le v, \forall r \in R \tag{7}$$

$$x_{sw}^r \ge 0, x_{wk}^r \ge 0, u_{kr} \ge 0, \forall s \in S, \forall w \in W, \forall k \in K, \forall r \in R \tag{8}$$

$$y_w \in \{0,1\}, \forall r \in R \tag{9}$$

$$Z \ge Cost_r(y,x,u), \forall r \in R \tag{10}$$

Equation (1) defines the min-max objective, through which the model seeks to minimize the worst-case total cost across all disruption scenarios. Equation (2) specifies the scenario-dependent total cost structure, which aggregates warehouse activation costs, transportation costs, and penalty costs associated with unmet shipyard demand. Equation (3) enforces supplier capacity limits, while Equation (4) imposes capacity constraints on warehouses that are activated in the network. Equation (5) enforces flow conservation at each warehouse by ensuring that the total inbound flow from suppliers equals the total outbound flow to shipyards in each scenario. Equation (6) ensures the satisfaction of scenario-based shipyard demand through inbound shipments or unmet-demand quantities. Equation (7) constrains total cost in each scenario to remain within a predefined allowable budget. In the numerical study, v is used as a sufficiently large feasibility-oriented upper bound and does not act as a binding budget constraint in the reported solutions. Equation (8) establishes the robust requirement by forcing the objective variable to dominate all scenario costs, ensuring that the final solution corresponds to the worst-case outcome. Equation (9) defines the binary nature of warehouse activation decisions, and Equation (10) connects the robust objective to scenario costs through the min–max structure.

Demand uncertainty is represented through two discrete demand scenarios, r_1 and r_2, and an uncertainty level $l \in \{0,1,\dots,10\}$. For each shipyard k, d_k^0 denotes the nominal demand. Scenario-specific demand levels are generated as follows:

$$d_{kr_1}(l) = d_k^0, \forall k \in K, \forall l \in \{0, \dots, 10\} \tag{11}$$

$$d_{kr_2}(l) = (1 + 0{,}002l)d_k^0, \forall k \in K, \forall l \in \{0, \dots, 10\} \tag{12}$$

Robust counterpart explanation

The robust counterpart of the proposed model is constructed by embedding scenario-based demand uncertainty directly into the nominal deterministic formulation. In the nominal structure, Equation (2) defines the total cost under a single deterministic demand realization. However, shipyard demand is not constant under ripple-effect conditions, and therefore a single deterministic constraint is insufficient to ensure feasibility and reliable performance when the system is exposed to disruptions. To address this limitation, additional constraints representing alternative demand realizations are introduced, and the total cost expression is evaluated independently for each scenario.

Equation (11) corresponds to the nominal demand case and reflects the baseline material requirement of each shipyard. Equation (12) represents the disrupted case, where demand is scaled proportionally according to the uncertainty level l. For each uncertainty level, the demand of scenario r_2 is generated by applying a controlled amplification rate of 2% per level, reaching up to a maximum increase of 20% when l = 10. This structure enables the model to evaluate the system under a sequence of progressively deteriorating conditions, capturing the escalation effect that is typical of ripple-effect propagation. The 2% incremental demand increase is used as a controlled stress-testing mechanism rather than as an empirically estimated disruption probability. This setting allows the model response to be observed under gradually worsening demand conditions, from the nominal case to a 20% demand increase. The two-scenario structure is selected to maintain transparency in the baseline formulation: r_1 represents normal operating conditions, whereas r_2 represents a disrupted demand state. This structure can be expanded by adding more scenarios when real shipyard data become available. In the robust formulation, the min-max objective in Equation (1) is activated by replacing the single deterministic cost expression with the scenario-dependent cost structure of Equation (2) and by imposing the robust bound in Equation (8). This constraint forces the objective variable Z to dominate all scenario-specific costs, thereby ensuring that the worst-case total cost governs the final solution. By adopting this structure, the model protects against systematic underestimation of demand and preserves feasibility across multiple disruption scenarios. Unlike classical robust optimization approaches that require additional auxiliary variables or an explicit uncertainty budget, the proposed formulation achieves robustness exclusively via alternative scenario costs and a dominating objective variable. As a result, the model delivers a conservative yet computationally tractable protection mechanism without introducing additional combinatorial complexity. The resulting robust counterpart therefore evaluates supplier–warehouse–shipyard flows under both nominal and stressed demand conditions and identifies warehouse activation and material flow decisions that remain stable and feasible across all demand realizations considered.

Overall, the robust counterpart integrates uncertainty into the model by substituting the deterministic demand constraint with scenario-specific demand values and by enforcing a worst-case protection mechanism through the min-max structure. This integration ensures that the network design remains feasible and cost-effective even when shipyard demand intensifies due to disruptions, thereby representing the cost of robustness embedded within the optimal solution.

3. Results

The numerical analysis is conducted using the illustrative shipbuilding supply chain instance defined in Section 2. The test network consists of three suppliers, three candidate warehouses, and eight shipyards. The parameter values are selected to create a balanced test setting in which capacity, transportation cost, warehouse activation cost, and unmet-demand penalty jointly influence the solution. Supplier capacities are set to 40, 45, and 50 units, respectively, while each warehouse has a capacity of 60 units. These values prevent the network from becoming either trivially feasible or infeasible under increasing demand. Warehouse activation costs are defined as 100, 110, and 120 to represent cost heterogeneity among candidate locations. The unmet-demand penalty is set to 100 per unit to discourage shortages when feasible shipment alternatives exist. Transportation costs are distance-based and computed as 0.8 × distSW for supplier–warehouse flows and 1.2 × distWK for warehouse–shipyard flows. Baseline shipyard demand is fixed at 10 units, except for k_1 and k_2, where nominal demand is set to 12 and 14 units, respectively. All tests are performed in GAMS with the CPLEX solver, and the performance of the robust model is evaluated across uncertainty levels ranging from 0 to 10. The results indicate that the worst-case objective value rises steadily as the uncertainty level increases. This trend directly reflects the growing material requirements at the shipyards: higher scenario demand leads to additional transportation activity and larger unmet-demand penalties, which collectively raise the cost captured by the robust objective value. A detailed summary of these outputs across all uncertainty steps is provided in Table 1, which reports the progression of worst-case costs together with the corresponding warehouse activation patterns and supplier engagement decisions. Across all uncertainty settings, the model consistently activates the same two warehouses and utilizes all three suppliers. This stable configuration suggests that, within the scope of the illustrative instance, the robust solution does not rely on repeated changes in facility activation decisions. Instead, the model absorbs increasing demand pressure through operational adjustments in shipment quantities and unmet-demand levels. Therefore, the predictable increase in the worst-case cost should not be interpreted as a weak result, but as the expected cost of maintaining feasibility under progressively severe demand conditions. In this sense, the increase in Z represents the price of robustness embedded in the min–max structure. For shipbuilding clusters such as Tuzla and Yalova, this finding is practically relevant because warehouse activation is a strategic decision, whereas shipment quantities can be adjusted more flexibly during disruption periods.

A comparison of scenario-based costs shows that the inflated scenario (r_2) always produces higher total costs than the nominal scenario (r_1), and the gap between the two scenarios widens as uncertainty increases. This behavior illustrates how increasing disruption severity amplifies downstream demand pressure and progressively pushes the system toward its capacity limits.

At each uncertainty level, the robust objective value coincides with the r_2 outcome, confirming that the model correctly identifies and protects against the most adverse cost scenario. Overall, the numerical findings demonstrate that the proposed framework maintains a balanced trade-off between feasibility and resilience. While the network structure remains unchanged, the system responds predictably to increasing disruption intensity, and the steady progression of worst-case costs highlights that robust planning inherently requires accepting higher operational expenditures as protection levels increase. These insights confirm that the proposed model effectively supports strategic decisions on warehouse activation and material flow allocation under ripple-effect conditions in shipbuilding supply chains.

To further examine the stability of the warehouse activation decision, a limited sensitivity analysis is conducted for the unmet-demand penalty at the highest uncertainty level (*l=10*). As shown in Table 2, the lower penalty value leads the model to activate only warehouse 1 and accept unmet demand in the disrupted scenario. In contrast, the base and higher penalty values result in the selection of warehouses 1 and 2, the use of all three suppliers, and zero unmet demand in the disrupted scenario. This finding indicates that the selected warehouse configuration becomes more robust when shortage avoidance is prioritized.

Table 1. Numerical results

Uncertainty level *(l)*	Worst-case cost *(Z)*	Selected warehouses *(W)*	Active suppliers *(S)*
0	6002.80	1,2	1,2,3
1	6130.02	1,2	1,2,3
2	6257.23	1,2	1,2,3
3	6384.45	1,2	1,2,3
4	6511.66	1,2	1,2,3
5	6638.88	1,2	1,2,3
6	6766.10	1,2	1,2,3
7	6893.31	1,2	1,2,3
8	7020.53	1,2	1,2,3
9	7147.74	1,2	1,2,3
10	7274.96	1,2	1,2,3

Table 2. Sensitivity analysis for unmet-demand penalty al *l=10*

Penalty cost	Worst-case cost	Selected warehouses	Active suppliers	Unmet demand in disrupted scenario
80	7173.60	1	1,2	43.20
100	7274.96	1,2	1,2,3	0.00
120	7274.96	1,2	1,2,3	0.00

4. Conclusion

This study presents a scenario-based robust optimization model designed as a preliminary step toward a two-stage stochastic optimization framework for shipbuilding supply chains. The proposed model captures demand uncertainty under disruption conditions and aims to establish a structurally stable and reliable network configuration before introducing more advanced stochastic decision layers.

The formulation represents a two-echelon material flow network from suppliers to intermediate warehouses and subsequently to shipyards. Demand uncertainty is incorporated through discrete scenarios, and robustness is ensured by minimizing the worst-case total system cost. This structure allows the supply chain to remain feasible under elevated demand levels without the need for scenario-specific recourse decisions.

Numerical results show that the worst-case cost increases gradually as demand uncertainty intensifies, reflecting higher material requirements and the associated growth in transportation and shortage penalty costs. Despite this increase, the set of activated warehouses and engaged suppliers remains invariant across all uncertainty levels. This outcome indicates that the robust structure primarily adapts through adjustments in material flow quantities rather than changes in the facility configuration.

The worst-case objective value consistently aligns with the most severe demand scenario, confirming that the min–max formulation effectively captures the system's exposure to disruption risk. Overall, the findings demonstrate that a stable, interpretable, and computationally tractable robust baseline can be established for shipbuilding supply chains operating under ripple-effect conditions.

This robust model constitutes the foundational modeling layer of an ongoing two-stage stochastic optimization study. Although the numerical instance is illustrative and intentionally compact, it provides a transparent basis for examining the behavior of the proposed robust formulation. Future research will extend this structure using real shipyard data, larger regional networks, additional disruption scenarios, and two-stage stochastic recourse decisions.

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Infrastructure of the Port of Poti: Current Condition, Key Constraints, and Strategic Prospects for Modernization

Nanuli Charbadze[1]*, Natalia Jijavadze[1]

[1] Batumi State Maritime Academy, Georgia

* Corresponding author: n.charbadze@bsma.edu.ge

Abstract. This paper presents a comprehensive assessment of the infrastructural, operational, and technological condition of the Port of Poti, Georgia's principal maritime gateway. The research evaluates the port's hydrotechnical parameters, cargo-handling capabilities, warehousing capacity, transport accessibility, and level of digital integration. Statistical data for 2019–2025 are analyzed to identify trends in container throughput, general and bulk cargo handling, and Ro-Ro operations. The findings indicate that insufficient navigational depth, aging lifting equipment, limited storage infrastructure, and the absence of an integrated digital ecosystem significantly constrain the port's competitiveness in the Black Sea region. The study evaluates the port's performance with reference to international standards established by UNCTAD, IMO, EMSA, and the World Bank. Strategic recommendations focus on dredging and channel expansion, modernization of cargo-handling equipment, terminal development, digital transformation through a Port Community System, and environmental sustainability measures.

Keywords: port infrastructure, maritime logistics, containerization, dredging, digitalization.

1. Introduction

The Port of Poti is the largest and most operationally diverse seaport in Georgia, acting as a gateway connecting the South Caucasus, Central Asia, and the Middle Eastern economies with global maritime trade networks. Its strategic location on the eastern coast of the Black Sea provides the port with a vital role within the Trans-Caucasian corridor and the Middle Corridor (Trans-Caspian International Transport Route). International maritime organizations, including UNCTAD and IMO, identify the port as an essential multimodal node whose efficiency directly influences regional cargo flows.

Despite its strategic advantages, the port faces a series of structural, technological, and organizational constraints that limit both operational productivity and long-term competitiveness. These include restricted navigational depths, aging cargo-handling equipment, insufficient warehousing facilities, road congestion, and a fragmented digital environment. This study seeks to address several research questions:

- What are the structural and operational limitations affecting the port's performance?

- How do these limitations correlate with observed cargo throughput trends?
- What modernization strategies would enable sustainable growth and alignment with international standards?

The study's relevance is supported by the growing strategic importance of the Middle Corridor, evolving logistics dynamics in the Black Sea region, and increasing global competition among medium-size ports.

2. Literature Review

The international literature on port competitiveness emphasizes five structural determinants: hydrotechnical parameters (depth, width, and navigational safety), terminal and superstructure capacity, digitalization level, hinterland connectivity, and regulatory efficiency (Martín-Navarro et al., 2020; Hakimi et al., 2025; World Bank & S&P Global Market Intelligence, 2024).

Studies by UNCTAD underline the importance of navigational depth as a critical bottleneck for medium-size ports facing sedimentation and seasonal fluctuations. Research from EMSA highlights safety and environmental considerations in ports where aging equipment remains in operation. Digitalization trends, including the implementation of Port Community Systems and AI-based port process optimization, are extensively analyzed in the works of Khazzar et al. (2025) and the annual reports of IMO.

Regional literature on Georgian ports, although limited, indicates persistent infrastructural disparities across the Black Sea basin, with most ports undergoing modernization to increase container handling capacity and support growing regional supply chains.

The review demonstrates that modernization of navigational infrastructure, handling equipment, and digital platforms is central to improving port performance—precisely the areas where the Port of Poti exhibits its most critical shortcomings.

3. Methodology

The study employs a mixed-methods approach integrating:

3.1 Quantitative Analysis

Statistical data for 2019–2025 sourced from Geostat, APM Terminals, shipping statistics, and public reports.

Time-series analysis of container, bulk, and Ro-Ro cargo flows.

Comparative evaluation using international performance indicators and publicly available port statistics.

3.2 Qualitative Operational Assessment

Technical review of dredging operations, superstructure performance, warehousing conditions, transport accessibility, and digitalization level.

Assessment based on publicly available technical documentation, industry reports, and regulatory publications.

3.3 International Comparative Assessment

Cross-comparison with recommendations and performance indicators published by UNCTAD, IMO, EMSA, and the World Bank.

The collected data were analyzed using descriptive statistical methods and comparative analysis to identify the principal infrastructural and operational constraints affecting the Port of Poti and to formulate strategic modernization priorities.

4. Results and Analysis

4.1 Navigational Constraints

Despite recent dredging activities and improvements in channel maintenance, navigational depth remains one of the principal operational constraints affecting the Port of Poti. Variations in channel depth and periodic sedimentation limit the reception of larger vessels and reduce operational flexibility. These conditions may contribute to vessel waiting times, increased freight costs, and reduced competitiveness compared with deeper Black Sea ports.

The figure 1 illustrates indicative operational depth ranges reported in publicly available port specifications, navigational notices, and technical documentation. For 30 April 2025, approved depths ranged from approximately 10.2 m to 10.5 m depending on the segment of the fairway, with working draft limits determined accordingly (Trans Logistic LLC declaration, 2025).

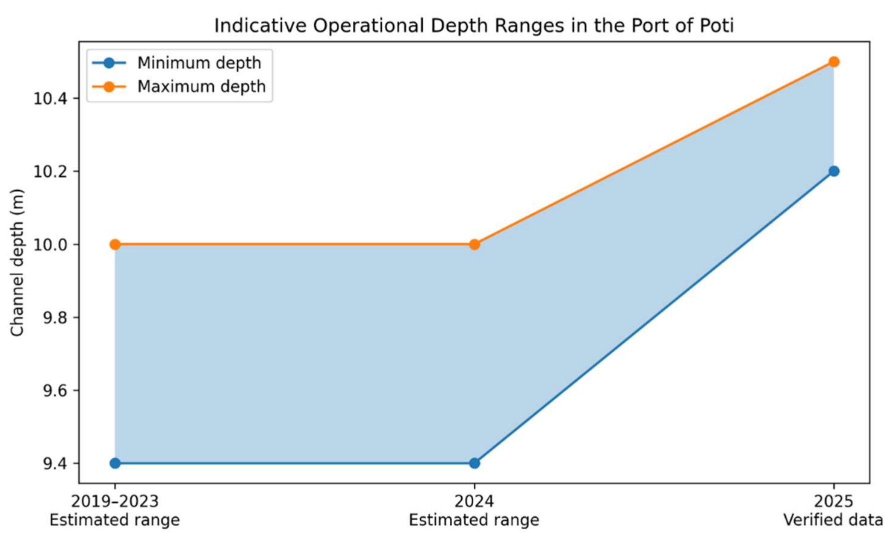

Figure 1. Estimated operational depth ranges and navigational limitations of the Port of Poti based on available port specifications, navigational notices, and verified 2025 channel depth data. Sources: Martín-Navarro et al. (2020); Hakimi et al. (2025).

Historical values presented for 2019–2024 represent estimated operational depth ranges derived from publicly available port specifications and technical documentation. Verified channel depth information for 2025 is based on officially reported navigational data. The figure is intended to illustrate general navigational constraints rather than provide a complete empirical time-series dataset.

4.2 Cargo-Handling Superstructure

The port relies heavily on TAKRAF cranes (1970s), characterized by:

- limited maneuvering speed,
- insufficient lifting capacity,
- high downtime due to maintenance,
- poor adaptability to modern containerized operations.

Modern cranes produced by Tonghui Machinery demonstrate 2–3× higher operational efficiency, lower energy consumption, and greater versatility.

Table 1. Comparative Technical Characteristics of Legacy TAKRAF Cranes and Modern Multi-Purpose Port Cranes. Source: Martín-Navarro et al. (2020); Hakimi et al. (2025).

Parameter	TAKRAF Crane	Modern multi-Purpose Crane
Lifting Capacity	10–16 t	40–65 t
Container Handling Capability	Limited	Full capability
Automation Compatibility	Low	High
Energy Efficiency	Low	High
Maintenance Requirements	High	Moderate
Operational Flexibility	Low	High
Cargo Type Adaptability	Limited	High

Data represent typical performance ranges; modern cranes demonstrate improved lifting capacity, operational speed, automation potential, adaptability to diverse cargo types, and energy efficiency relative to older models.

4.3 Warehousing and Environmental Conditions

Current open storage facilities accommodate approx. 25,000 tons, with daily throughput around 3,000 tons - far below regional averages. Open-air operations increase environmental risks, including dust emissions from fertilizers and bulk materials, affecting workers and nearby communities.

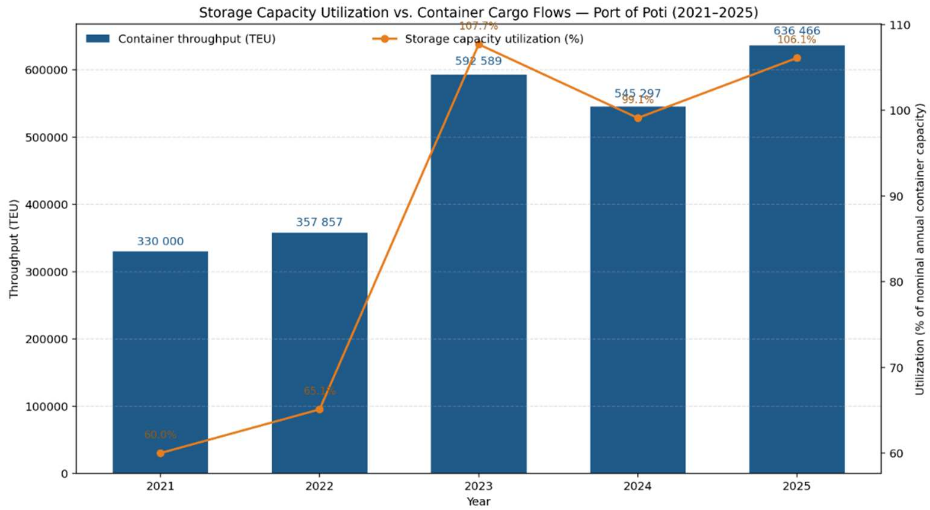

Figure 2: Storage capacity utilization vs. cargo flows (2021–2025). Source: Geostat (2024); APM Terminals Poti operational statistics.

4.4 Comparative Benchmarking

To assess the relative position of the Port of Poti within the Black Sea region, a comparative benchmarking analysis was conducted using selected infrastructural and operational indicators. The comparison includes the ports of Poti, Batumi, and Constanța, which represent different levels of infrastructure development and regional competitiveness.

Table 2. Comparative Infrastructure Indicators of Selected Black Sea Ports. Source: UNCTAD (2024); World Bank & S&P Global Market Intelligence (2024); official port data.

Indicator	**Poti**	**Batumi**	**Constanța**
Maximum Operational Depth (m)	10.5	14.0	19.0
Container Capacity (TEU/year)	500,000	100,000+	1,500,000+
Port Community System	Planned	Partial	Implemented
Modern Crane Infrastructure	Partial	Moderate	Extensive

The comparison demonstrates that although the Port of Poti benefits from a strategically important geographical location within the Middle Corridor, it remains constrained by limited navigational depth, partially modernized cargo-handling infrastructure, and a lower level of digital integration compared with leading Black Sea ports. These factors highlight the importance of continued investment in dredging, terminal modernization, and digital transformation initiatives.

4.5 Road and Hinterland Connectivity

The efficiency of cargo movements through the Port of Poti is significantly influenced by the quality of hinterland transport connections. At present, a substantial share of cargo traffic relies on municipal road infrastructure, creating operational bottlenecks and limiting the efficiency of port-related logistics activities. Road congestion, insufficient scheduling flexibility for truck operations, and growing traffic intensity contribute to longer cargo dwell times and increased transportation costs. In addition, the concentration of freight traffic within urban areas generates environmental pressures through higher emissions, noise, and road wear.

Digitalization Level

Recent implementation of the Maritime Single Window (MSW) has improved the efficiency of vessel reporting procedures and facilitated compliance with international reporting requirements. However, cargo-related information flows remain fragmented across multiple stakeholders, limiting overall process transparency and coordination. The introduction of a Port Community System (PCS) would enable greater integration of port authorities, terminal operators, customs agencies, freight forwarders, and shipping companies. Such a system could reduce administrative burdens, improve information exchange, enhance operational transparency, and contribute to shorter cargo processing and dwell times.

Table 3. Functional Comparison of MSW and PCS. Source: UNCTAD (2024); IMO (2024).

Function	MSW	PCS
Vessel Reporting	✓	✓
Customs Integration	Limited	Full
Cargo Management	✗	✓
Logistics Coordination	✗	✓
Stakeholder Integration	Partial	Full

The comparison demonstrates the functional differences between the Maritime Single Window (MSW) and the Port Community System (PCS). MSW primarily standardizes mandatory maritime reporting and document submission processes within port calls, whereas PCS extends digital integration to include operational, logistical, and commercial functions across the entire port ecosystem. The two systems can be integrated, with PCS incorporating MSW modules while providing broader functionality for port community stakeholders.

5. Discussion

The analysis reveals a systemic pattern: the port's key constraints reinforce each other. Shallow depths restrict vessel size, which discourages liner services from routing through Poti. Aging terminal equipment slows cargo processing, limiting economies of scale. Insufficient warehouses create bottlenecks during seasonal peaks. Poor road connectivity extends dwell times, and a fragmented digital environment exacerbates coordination inefficiencies.

From a regional perspective, the port risks losing competitive advantage to neighboring facilities undergoing substantial modernization. Aligning infrastructure with international standards is no longer optional - it is a prerequisite for participating in evolving global supply chains and ensuring long-term sustainability of Georgia's transit function.

5.1 Recommendations

The modernization of the Port of Poti requires a comprehensive and integrated development strategy addressing both infrastructural and organizational constraints. Priority should be given to further dredging activities aimed at increasing basin and channel depths to approximately 10.5 m. In parallel, the acquisition of high-capacity dredging equipment would support the long-term maintenance of navigational parameters and reduce sedimentation-related operational limitations.

Another important direction concerns the modernization of cargo-handling infrastructure. The phased replacement of aging TAKRAF cranes with modern multi-purpose cargo-handling equipment would improve operational productivity, reliability, energy efficiency, and adaptability to contemporary containerized cargo operations.

Future development should also include the expansion of terminal and storage infrastructure. Increasing container terminal capacity to approximately 500,000 TEU annually, together with the construction of covered warehouses equipped with dust-suppression systems, would enhance operational efficiency while simultaneously improving environmental performance.

The efficiency of the port is closely linked to the quality of hinterland transport connections. Investments in road infrastructure, dedicated truck corridors, and digital vehicle scheduling systems could significantly reduce congestion and improve cargo flow efficiency between the port and inland transport networks.

Digital transformation should be considered a strategic priority. The implementation of a full-scale Port Community System (PCS) would strengthen coordination among port authorities, terminal operators, customs agencies, freight forwarders, and shipping companies, thereby improving transparency, information exchange, and overall operational efficiency.

Finally, environmental sustainability should remain an integral component of future development. The adoption of EU-aligned emission control measures, green port initiatives, and enhanced environmental monitoring practices would contribute to improving environmental performance and supporting the long-term sustainable development of the port.

6. Conclusion

The Port of Poti holds significant geopolitical and economic importance within the Black Sea and Trans-Caucasian transport networks. However, a combination of hydrotechnical, technological, infrastructural, and organizational challenges constrain its ability to meet growing regional demand. Strategic investments in dredging, modernization of superstructure, warehousing expansion, digitalization, and environmental safety are essential to align the port with contemporary global standards. Implementation of these measures will enhance throughput, strengthen the port’s role in regional logistics, and elevate Georgia’s position in transcontinental trade routes.

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The sea routes, between security, geopolitical criticalities, religious tensions and economic interests

Vasco Fronzoni*

Pegaso University, Italy

* Corresponding author: vasco.fronzoni@unipegaso.it

Abstract. This article examines maritime routes as strategic infrastructures at the intersection of economic interdependence, security imperatives, religious tensions, and geopolitical competition. Starting from a historical and theoretical overview of sea power, it highlights how control of maritime communication lines has evolved from a primarily military doctrine into a multidimensional instrument encompassing legal, economic, and political dimensions. The study analyzes the structural fragility of the global maritime system, emphasizing the role of critical choke points and submarine infrastructures in sustaining international trade, energy supplies, and digital connectivity. Particular attention is devoted to contemporary crisis areas, including the Red Sea, the Strait of Hormuz, the Baltic Sea, and the Mediterranean, where state and non-state actors increasingly exploit maritime vulnerabilities through hybrid and asymmetric strategies. The Houthi insurgency, disruptions to submarine cables and pipelines, and recent incidents involving energy and data infrastructure are discussed as emblematic cases of emerging maritime insecurity. The article also explores national responses, with a focus on Italy's strategic repositioning within the framework of the "enlarged Mediterranean" and recent legislative developments aimed at protecting underwater assets. Ultimately, the contribution argues that maritime routes are no longer neutral spaces but key arenas in which global power balances, legal regimes, and security architectures are being reshaped

Key Words: Maritime security; Sea power; Geopolitical choke points; Submarine infrastructures; Hybrid warfare

1. Introduction: The historical importance of the sea routes.

Navigation emerged as humans developed the capacity to construct vessels, plot courses, navigate waves, utilize currents, and sail against winds. Since then, humanity has traversed sea routes for exploration, conquest, exchange, trade, migration, colonization, and, subsequently, for the procurement of raw materials from quarries and mines. Consequently, sea routes have become pivotal catalysts for development and power.

If we retrace the history of humanity, in fact, we can easily notice how the main civilizations arose precisely along the coastal strip and how they managed to flourish by developing maritime skills and sailing the seas.

Currently, oceans cover 70% of the Earth's surface, with 80% of the global population concentrated near coastlines. It is important to note that the majority of global production activities occur at sea, underscoring the critical importance of maritime navigation for international trade. The globalization of the economy has fostered significant interdependence among countries, even those geographically distant, as they are interconnected within the producer-processor-consumer chain. The continuous flow of goods and energy resources facilitates this continuity. According to the European Maritime Safety Agency, today, 90% of these goods and raw materials transit along maritime communication lines, and 75% of this flow passes through critical geographical nodes, known as "choke points", which are international canals and straits often subject to international disputes.

In the contemporary era, sometimes termed the Anthropocene (Crutzen & Stoermer, 2000) to highlight humanity's profound impact on the Earth's environment and natural resource exploitation, entire economies rely on the uninterrupted flow of oil, gas, and container traffic. However, beneath the seemingly neutral surface of international waters lie strategic challenges, geopolitical rivalries, and hegemonic conflicts concerning the acquisition and distribution of these resources, leading to a dynamic reshaping of global balances.

Maritime routes serve not only as conduits for trade but also reflect the power dynamics and interests of states, thereby acting as indicators of international relations and geopolitical balances. The notion that control of the sea dictates the destiny of nations is a recurring theme in major theories of maritime power and geopolitics. This dominion over sea routes is conceptualized across three levels: physical control, exercised to guarantee freedom of navigation (e.g., mitigating maritime piracy); economic influence, implemented to protect trade flows; and soft power, utilized as a deterrent to foster alliances and establish international regulations.

2. The practical relevance of the concept of Sea power

The concept of maritime power originated in the West during the Punic Wars, when Rome introduced significant innovations to its vessels, such as the "rostrum" and the "corvus" (Pitassi, 2015; Maniscalco, 1992). However, it developed substantially between the 16th and 18th centuries, during the "golden age" of navigation and exploration. This period of colonialism and maritime imperialism witnessed major naval powers vying for supremacy over the seas through a complex interplay of military, economic, and geographical factors.

Presently, maritime power is governed by International Maritime Law, yet its theoretical foundations lie in the works of classical authors whose insights, despite subsequent updates, continue to inform contemporary doctrine. The notion of "Sea Power" (Mahan, 2010; Corbett, 1988; Mackinder, 1902) thus pertains to a Nation's capacity to exert influence over the seas for political, economic, and military objectives. It is considered essential for projecting national power, controlling commercial maritime routes and strategic points, and serves as a prerequisite for geopolitical expansion and international supremacy.

When exercised through a combined control of land resources and sea routes, maritime power becomes a fundamental lever for global hegemony.

Therefore, maritime power has evolved from a purely military doctrine into a multifaceted instrument of strategic influence, relevant in both political-military and legal-economic dimensions. This evolution has contributed to redefining the very concept of maritime dominion, particularly in light of contemporary international law.

3. Maritime routes between economy and trade

All major global powers are actively expanding their zones of influence far beyond their territorial waters, extending strategic, economic, and military control even to distant maritime regions. A clear example is the People's Republic of China's strategic approach, which involves substantial investments in acquiring ports such as Port Said in Egypt and Piraeus in Greece. These ports are subsequently utilized as dual-use (civilian/military) bases, positioning China as a leading economic player in the Mediterranean. These acquisitions enable China to leverage its commercial power and infrastructural supremacy to counter any interference from competitors on sensitive issues.

The maritime system is undeniably fundamental, strategically contested, and intrinsically interconnected. A delay of a container ship in the port of Cartagena, for instance, can elevate the price of coffee in Naples. Simultaneously, however, the maritime system is also exceedingly fragile.

3.1 Suez Strait, Red Sea and the Houthi threat

A stark example of this intrinsic vulnerability was the 2021 Suez Canal crisis, when the container ship Ever Given ran aground, blocking the canal for over a week and causing immense negative repercussions on global trade (Shen, 2025; Khoi et al., 2025).

The Red Sea undoubtedly represents a strategic naval artery. Thanks to pioneering infrastructure projects like the Suez Isthmus and the construction of the Ras Bir lighthouse in the Strait of Bab al-Mandeb and the Crispi lighthouse at Cape Guardafui, the Red Sea has progressively become a vital highway for merchant traffic, essential for global logistics. Furthermore, this sea is known to host a dense network of submarine cables, crucial for a substantial portion of the world's data traffic, and equally threatened by the Houthi insurgency.

Following the Suez Canal obstruction, the Red Sea has been subject to an ongoing crisis since 2023, stemming from the threat of attacks on vessels transiting from Yemen by the Houthis. These attacks have resulted in significant global repercussions, increasing insurance costs, substantially slowing goods delivery, and compelling shipping companies to seek alternative routes.

But who are the Houthis, and what are their objectives?

The transformative movements of the "Arab Springs" also impacted the Republic of Yemen and this led to the 2012 deposition of Ali Abd Allah Saleh, former President of North Yemen and the first President after unification—who had been in power for over thirty years. This deposition destabilized the country, soon leading to a civil war, formally declared on an inter-confessional basis between Sunni and Shi'ite religious factions, but with broader, still unresolved motivations. The conflict's consequences are disastrous, particularly for the civilian population, which even before the hostilities was already classified as among the world's poorest (Dresch, 2000).

The division between tribal clans represent also a division at the confessional level, as Yemen, unlike other Islamic countries, has an almost balanced presence of Sunnis (particularly Shafi'ites) and Shi'ites (predominantly of the Zaydi school), to which Houthis belongs.

The current Republic of Yemen emerged from the country's unification on 1990, that led to the cohabitation of two very distinct historical, political, economic, and social realities, also separated by their adherence to different legal schools.

The Shi'it Houthi movement's activism as a dissident group began in the 1990s from the capital and rapidly spread across much of the country, culminating in an armed rebellion against the central government, and in 2014 they conquered the capital Sana'a. Since then, they have become major regional actors, adopting an anti-Western and anti-Sunni mood.

Today, the Houthi threat has significantly disrupted shipping routes in the Red Sea, increasing the cost and time for shipping and delivery of goods. It has also exposed a critical vulnerability in the global submarine cable infrastructure, underscoring the need for enhanced protection and prompting the deployment of international military missions such as the US-led "Prosperity Guardian" and the European-led "Aspides", to protect maritime traffic.

The Strait of Hormuz represents the sole access to the Persian Gulf area and, critically, the only viable route for transporting of crude oil demanded by global markets. This is due to the unique geography of the Persian Gulf, the immense volume of oil production from major regional producers, and the limited capacity of alternative transport routes. Each day, approximately 20% of global demand passes through the Strait as well as 30% of the world's marketed liquefied natural gas.

In 2010, following the official announcement of a significant increase in enriched uranium production at Iran's Natanz nuclear power plant, a nuclear crisis erupted (Ofek, 2021). This led to an intensification of embargoes and "Western" sanctions on Iran, which had been in effect since 1996, resulting in a decline in Iranian oil production and exports to third countries, with unavoidable global repercussions. Following the outbreak of the conflict between Israel and Iran in 2025, it is easy to foresee enormous repercussions: oil traffic through the Strait of Hormuz and its control will be decisive in both local scenarios and global balances.

4. Hybrid warfare and protection of strategic infrastructures

Almost all global internet traffic is transmitted via undersea cables. Inevitably, the theory of maritime power extends to the oceanic regions traversed by these cables. The current expansionist strategies of states and international tensions render their control and security precarious, thus jeopardizing the connections upon which the global economy now relies.

The risks involve both accidental damage, despite advanced construction and installation techniques, and potential sabotage or targeted attacks during conflicts. There is also the possibility that these cables could be exploited for espionage and cyberattacks (Bueger et al., 2022; Burnett, 2021). Furthermore, issues of litigation between public and private entities arise, as does the question of sovereignty that countries can exercise over these infrastructures, given that most cables are owned by private companies or "Big Tech" corporations (García Cáceres, 2023; Raha & Raju, 2021). The considerations regarding undersea cables are largely applicable to submarine gas pipeline systems, where similar risks and problems exist (Pogoretskyy, 2017).

Since 2022, the Baltic Sea has been the site of a series of incidents involving strategic submarine infrastructure, prompting strong suspicions of sabotage and reigniting the debate on the safety of submarine cables and pipelines, as well as the concept of "hybrid warfare" (Hoffman, 2007). This term generally refers to a conflict strategy that simultaneously and coordinately integrates various modes of aggression, transcending the traditional distinctions between conventional and irregular warfare. Actors who adopt this strategy, whether state or non-state, combine military tactics with non-military actions and tools, often employed undeclared or ambiguously, to achieve political or strategic objectives, even resorting, in the case at hand, to sabotage or attacks (Muuga et al., 2025).

Key events include the sabotage of the Nord Stream 1 and 2 pipelines in September 2022 and investigations have ruled out accidental damage but have not definitively identified specific responsibility. In October 2023, the Balticconnector pipeline, connecting Finland and Estonia, and an associated communication cable were damaged. Between November and December 2024, several submarine telecommunications and energy cables laid in the Baltic Sea were interrupted, including those connecting Finland to Germany (C-Lion-1), Sweden to Lithuania, and the EstLink 2 power cable between Finland and Estonia. Once again, investigations focused on the possibility of sabotage.

Investigations have ruled out accidental damage but have not definitively identified specific responsibility although suspicions for most incidents have been directed at an alleged "Russian shadow fleet" operating in the area. The threat has significant implications for Europe and global connectivity (Lee, 2025).

5. The Italian Navy's strategy in the "enlarged Mediterranean"

Mediterranean holds particular relevance. Despite comprising only 1% of the global water surface, it is traversed by nearly 20% of the world's maritime traffic. Italy, a nation with a strong maritime character, possessing approximately 8,000 km of coastline and a distinctive morphology, is centrally located in the Mediterranean. It is Europe's leading country for the volume of goods imported by sea, and also imports approximately 80% of its oil needs via maritime routes. The national maritime cluster alone generates about 3% of Italy's GDP, with an economic multiplier equal to 2.9 times the invested capital (Nomisma, 2021).

To ensure natural gas supplies to countries like Italy and Spain (and, through them, to the rest of Europe), specialized terminals for liquefied gas transport and hundreds of kilometers of gas pipelines are necessary, many of which cross multiple countries and the Mediterranean Sea itself (Fabbri, 2020; Sellari, 2021). These combined circumstances have led to a redefinition of Italian maritime strategy, prompting first the Italian Navy and then the Government to conceive an "enlarged Mediterranean" (Ramoino, 1999). This concept defines an "operational theater of maximum national interest in which the Italian State implements a common security strategy" (Domini, 2022). The enlarged Mediterranean thus constitutes a zone of political, economic, and security projection that incorporates into Italy's strategic space a vast area spanning the Strait of Gibraltar, the Black Sea, parts of the Indian Ocean, parts of the Atlantic Ocean, and the Persian Gulf, thereby also including the Middle East and Central Africa (Jean, 1995). The protection and stability of the Mediterranean Sea and its extended projections are crucial for Italy and for the entire European Union.

Recently, Italian Government has started a new strategy rooted in the notion of maritime power, amending its legislative and regulatory framework through Bill No. 1462/2025, titled "safety of underwater activities". Amending Military Code, the Italian Government drastically has modified the Italian Navy's rules of engagement, authorizing the Italian Navy to react by opening fire against any entity threatening the safety of underwater infrastructure of national interest.

An Agency for the Safety of Underwater Activities (ASAS) is also established, with transversal responsibilities, under the functional authority of the Presidency of the Council of Ministers. Its primary task is to define the measures necessary to ensure the physical safety of underwater structures in maritime areas under national jurisdiction and, limited to those of national interest owned by Italian nationals, also on the high seas. The Agency's other tasks include coordinating international and European cooperation in underwater matters, in conjunction with the Ministry of Foreign Affairs and International Cooperation and the Ministry of Infrastructure and Transport, as well as collaborating with intelligence and security agencies in exchanging information on the seabed and the status of strategic infrastructure.

6. Conclusions

An analysis of contemporary geopolitical dynamics confirms the inescapable importance of maritime power as a determining factor for national security and international stability. From its original formulation as a military doctrine, the concept of sea power has evolved into a complex instrument of strategic influence, permeating political-military, economic, and legal dimensions, and also informing the legal framework of reference. The architecture of international maritime law, founded on key conventions such as UNCLOS, while providing an essential regulatory framework for the regulation of maritime spaces and freedom of navigation, demonstrates the limits of its practical applicability in contexts of growing geopolitical tension. The proliferation of disputes and the dynamic interpretation of normative principles highlight an intrinsic tension between state sovereignty and the peaceful use of the seas, necessitating a recalibration of national strategies in light of the concept of maritime power.

Furthermore, the structural vulnerability of maritime lines of communication and tensions at critical chokepoints, such as the Strait of Hormuz and the Red Sea, are emerging as a focal point for global security. Crises generated by religious conflicts and geopolitical tensions, such as the ongoing friction between Iran and Sunni proxies, or the Houthi insurgency in Yemen, demonstrate how regional fragilities can have systemic repercussions on international trade and energy security. These scenarios require reflection on the effectiveness of defensive missions and the desirability of a more robust multilateral intervention, in accordance with customary and treaty international law.

An area of growing concern concerns the protection of strategic underwater infrastructure, namely telecommunications cables and gas pipelines. Almost all global data traffic and a significant portion of energy transport depend on these facilities, making them primary targets in modern hybrid warfare. Events such as the sabotage in the Baltic Sea or the threatened blockade of the Strait of Hormuz not only reveal the physical vulnerability of such infrastructures, but also highlight the ambiguity and difficulty in assigning legal responsibility in the context of unconventional operations.

In this context, the Italian strategy, based on the idea of an “enlarged Mediterranean”, represents an approach consistent with the need to defend national interests in a strategic projection area. The proposed Italian regulatory reform through Bill 1462/2025, which amends the military system and establishes the Agency for the Safety of Underwater Activities (ASAS), reflects a paradigm shift in the application of the traditional concept of maritime power. It aims to provide a legal framework for effective military engagement aimed at protecting underwater infrastructure of national interest, including in the High Seas, and to improve international intelligence coordination.

Ultimately, safeguarding the maritime domain requires an integrated approach that combines compliance with the international legal framework with the necessary projection of force to ensure the uninterrupted continuity of vital flows, such as goods, energy supplies, and data. Global economic interdependence requires that maritime security be managed not only through the use of conventional means, but also through robust protection of critical underwater infrastructure, which must be conceived as external ramifications of the national territory, in terms of strategic security and as an extension of the notion of maritime power.

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Support and Career Development Platform for Georgian and Worldwide Maritime Graduates

Guladi Tkhilaishvili[1]*, Ketevan Tchanidze[1], Manuchar Loria[1], Eldar Mskhaladze[1]

[1] Batumi State Maritime Academy, Georgia

* Corresponding author: g.tkhilaishvili@bsma.edu.ge

Abstract: The article is a continuation of the research project "From Enterprise Resource Planning (ERP) to University Resource Planning (URP)" (AGA IAMUC 2022). A digital centralised system is essential for properly analysing and assessing the performance of administrative and academic staff.

In the proposed model, fundamental URP components include Financial Resource Management, Quality Assurance Management, Human and Assets Management, Marketing & PR Management, University Administration, Faculty Governance, Academic Activities, and Student Support and Career Development. Without consolidating and measuring these activities, Higher Education Institutions (HEIs) merely perceive aggregated information regarding weaknesses and gaps in achieving strategic or operational goals. The goal of the article was to study how to create a unified platform (portal and database) to support the URP's Student Support and Career Development component. The research studied Batumi State Maritime Academy's (BSMA) alumni, government, local, and international businesses in Georgia to assure their continuing connection via an integrated remote platform. The study also evaluated IAMU member HEIs graduates' challenges, opportunities, and labour market competitiveness. Currently, maritime universities individually sign memorandums of understanding with employers, but no centralised platform exists for ALL MEMBER UNIVERSITIES to serve both students and employers.

The objective was to study unified platform perspectives, propose the best alternative, and initiate a commonwealth system among IAMU partner universities to facilitate sharing job and career development information.

The research methodology relied on primary survey data, secondary data, and the analysis of quantitative and qualitative statistics.

In conclusion, the article detailed the development of an electronic platform and database that will assist students in finding jobs matching their specialisation and competencies. Concurrently, employers can use database filters to select students or graduates possessing the precise qualifications for their vacancies. Thus, the platform effectively connects maritime industry employers with qualified candidates.

Key words: Career Development; Students & Graduates Support; Employment Platform.

1. Introduction

Maritime shipping is one of the most widely used and effective types of transport in international freight operations. Maritime transport is also very important globally since it plays a crucial role in the emergence of a single international transport system of product transportation. Different from many other transport sectors where the business is carried out based on specific contracts, maritime transport belongs to the international shipping and logistics field.

Consequently, employment prospects for Georgian Maritime graduates include global positions in the maritime business of commercial shipping, offshore oil and gas, cruise lines, port management, and maritime logistics. Before graduating, they should make it their endeavour to have relevant certification, which is expected under the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW Convention). Once they secure these certificates, employment may be procured by one of the online recruitment sites, employment agencies, or direct application with shipping companies. Also, they can benefit from the academic networking, to attend conferences and exhibitions, get to know people belonging to the maritime field. COVID-19 has drastically affected the worldwide maritime industry by creating difficulties in crewing and employment; however, it is gradually recovering, and therefore, the worldwide employment opportunities for the Georgian Maritime graduates are also expected to rise with time as the industry recovers from all situations.

The advancement of maritime business specifically necessitates is the acquisition of higher standards of education. During the last 10 years, Georgia has been developing as an international centre of maritime logistics. Maritime education is becoming more developed, which can be illustrated by the constant increase in the percentage of students studying in maritime education programs and the number of educators' programs in national MET institutions. (MDPI open access journal 2021)

As stated in the Government Programme 2021-2024 (GoProgram 2021-2024), several initiatives are implemented to boost maritime employment and enhance the country's transport and logistics functions:

- The expected outcome will be the development of an online trading platform relating to international transport.
- Will continue to follow ICAO and European regulations.
- The possibility of applying the maritime single-window principle and the digitalisation of services related to Georgia's maritime sector will be examined by the country.
- Directing the Georgian seamen to get employed, ratification of the international maritime conventions, and development of the maritime educational systems.
- Financing of projects and the development of maritime transport and maritime structures will be supported. (EBRD 2021-2026)

- Help the Maritime Transport Agency in developing a Port Social Network in symbiosis with the MSW to support simplified supply chains as per the Government. (Maritime Transport Agency 2021)

2. Literature Review

The mission of the Maritime Transport Agency of Georgia is one of the main priorities of which is to promote employment of Georgian seafarers. Since 2021, the certificates for foreigners' competence of Georgian sailors have been acknowledged by the main counterpart countries, Saudi Arabia and the United Arab Emirates. Thus, Georgian seafarers have a right to work in the labour markets of 62 maritime countries, of which 22 are members of the European Union. According to Georgian statistics of sailors in 2021 – 2022, more than 8500 sailors entered the state border of Georgia for sailing. On average, the seafarers contributed $300 million in foreign currency to the country's economy. The relevance of large ship-owning companies towards Georgian sailors has increased significantly: For instance, in 2021-22 a tripartite memorandum was signed with the leading Singaporean ship owning company and the five famous ship owners of the country named, Eastern Pacific Shipping Pte. Ltd. (SOS operates 123 vessels, 42 of which are container carriers, the remaining vessels include a young generation of dry bulk carriers and tankers, and EPS directly employs over 5,000 people), where the achievement of company representatives, an annual list of students completed a six-month maritime internship. The flow of clients to receive a certificate of competence through passing the test in the period from January to December 2022 at the Maritime Transport Agency was 2142, but 1804 clients completed the test. Slightly different information can be received in the case of the interview: the number of passers amounted to 766 individuals, and the result by 80% was positive. (GEORGIAN MARITIME SCIENTIFIC JOURNAL 2021)

Over time, the global supply of officers and skilled seafarers in industrialised countries is dwindling in the international labour force. It also expects the prevalence of obvious competence in human capital shortage in the labour market by 2026, which will contribute up to 5% staffing deficit. The first and foremost is the relative inactivity of the seafarer profession in the affluent countries of the world. Marine agents, consultants and shipbuilding employees are sought after in the same countries' labour markets. Being responsible for around 80% of the global commodity transport, the maritime business stands among the most rapidly growing ones. General maritime commerce is expanding at a much faster rate than the world's population, which is why addressing these shortcomings and staff advancement is vital. Population in the global level and the availability and need for the market in the area influence the rate of growth of shipping. (ICMAT 2021)

3. Research results

On June 22, 2022, Batumi State Maritime Academy held the "Employers' Forum 2022" at the "Sheraton Batumi" hotel. Within the framework of the mentioned forum, we conducted a survey of employers; more than 26 local and international organisations participated in the survey and the purpose was to reveal the trends of the labour market, define the main problems and receive recommendations. (QAS 2022)

The indicators of employment of graduates of the undergraduate programmes of the three faculties of the Maritime Academy (the faculty of navigation, engineering, and business). A graduate of the Faculty of Navigation and Engineering cannot start working immediately after graduation. Since there is a lot of competition in the global labour market for employment in international companies, their employment rate is 38–60%. Business graduates are mainly employed in local organisations, which is reflected in the high level of employment (60–80%). According to the graduation rate, the Maritime Academy largely produces qualified students. (QAS 2022)

We assess the degree to which a graduate's knowledge and abilities satisfy the standards for the efficient performance of the organisation's operations.

As a result of our research (in Diagram N1), we observed that the knowledge and skills of our graduates are mostly in line with the requirements of organisations. The evaluation of organisations was distributed as follows: completely 15.4%, mostly relevant 53.8%, partially relevant 19.2%, and 11.5% replied that they do not yet have a graduate of the academy employed in their organisation. Through a personal interview, up to 70 percent of organisations are satisfied with the graduate. (QAS 2022)

With joint research by the Academy and us, we specified what knowledge, skills, and values graduates of the Maritime Academy should have for employment in certain companies.

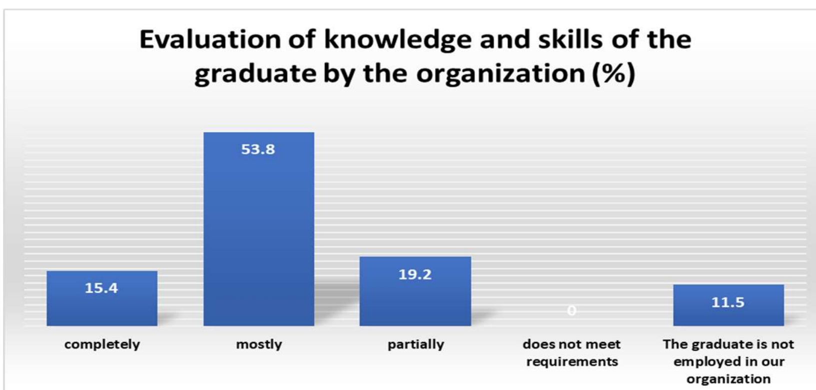

Diagram 1. Evaluation of knowledge and skills of the graduate by the organisation (%
Source: Evaluation of graduates by the employer, QAS, Batumi State Maritime Academy 2022

In the survey (Diagram N2), the respondents had the opportunity to prioritize the predetermined criteria that employers consider essential in the case of hiring graduates of the Maritime Academy. As a result, we can see that teamwork and the ability to constantly update knowledge (LLL), as well as knowledge of foreign languages, are the three main criteria that are determined in the applicant selection process.

Also, most of the respondents believe that the lack of qualified personnel in the labour market makes it difficult to find new staff in the current environment. Most interviewed employers are satisfied with the level of competence of the graduates of the Maritime Academy, while many of them note that, depending on the activities of their company, the graduates need additional qualification training/courses; only a part of them notes that there was no such need.

4. Analysis

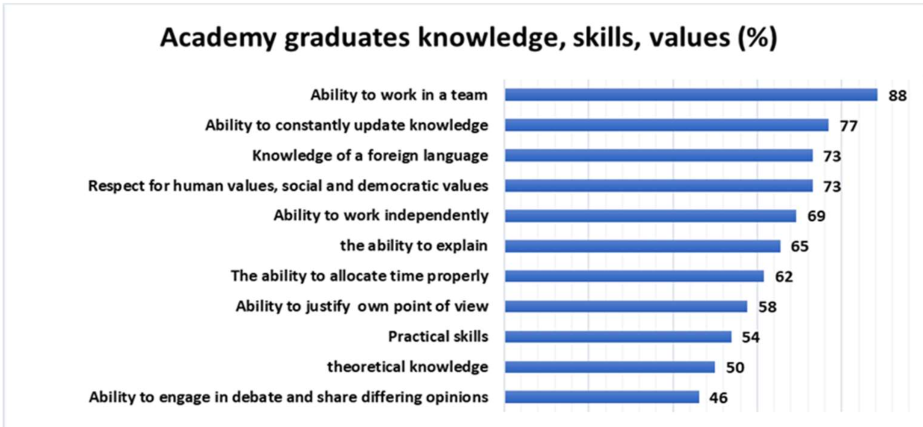

Diagram 2. Academy Graduates' knowledge, skills, and values (%)
Source: Evaluation of graduates by the employer, QAS, Batumi State Maritime Academy 2022

During the analyse global academic institutions, it can be assumed that there is a gap in demand for competent seafarers in the international labour market till 2025, and so Georgia, as a maritime country, will be able to respond to the requests on time.

In consequence, we must concern the necessity to identify the issues with the employment of students and graduates in the global and national economies.

Studies and analysis of numerous results of students also demonstrate that graduates from Georgian universities can be employed in foreign countries and can easily compete in the international labour market, but the maritime universities are mostly oriented to employ students of marine navigation and mechanical specialities. The overwhelming majority of the IMO's affiliated universities offer additional educational programs like business administration, Maritime economics, port management, logistics and forwarding, transport economics, Maritime and Cruise Tourism, and others, even though the employment opportunities for these courses are not properly promoted.

Even though maritime institutions are mainly aiming at placing students of maritime navigation and mechanical specialisations into the Georgian and foreign workplaces, research and students' evident success support the conclusion that Georgian graduates may compete and secure a job in the global labour market.

The BSMA graduates are competing in quite a different world characterised by certain challenges, opportunities, and competitiveness at the international labour market. Here are some of the key factors that can impact their career prospects:

Challenges:

- Few employment opportunities in specific areas or certain areas of the marine business.

- The key factor which has been identified as contributing to the maritime labour market is its highly competitive.
- A situation where to be qualified for a certain position, one needs to get extra certifications or a license.
- The strenuous and rigorous actions of some of the occupations in the maritime sector.

Opportunities:

- The opportunities of getting better jobs and chances to navigate to leadership positions within the companies in the business.
- The ability to enter a project with mass-market appeal that can make effective use of modern technology in its turn and actively participate in creating new methods.
- The possibility of competitive remuneration and added perks depending on the area of the industry.

Competitiveness:

- Global and local maritime industry organisations could be significant partners of IAMU member HEIs given that some of the institutions place their graduates to work directly with their employees.
- With a good reputation, IAMU member HEIs' graduates can easily find market themselves and be more likely to be chosen because of worldwide recognition.

All in all, IAMU member HEIs graduates are exposed to the constantly growing and highly competitive labour market but, at the same time, various opportunities and privileges are opening for them. Since IAMU member HEIs provide continued education for their graduates, networking/job placement services and being updated with current developments in the industry, their graduates will be well-suited in the global maritime industry market.

5. Conclusion

The factors that could influence labour market competitiveness, opportunities, and challenges for graduates may be numerous and diverse for member higher education institutions of the International Association of Maritime Universities. They may be related to a field of study, a geographical region, or general economic conditions in a country.

in our article we aim to present not a theoretical model, but to introduce the idea of a commonwealth real-life job occupation portal. Although the partner university member information data cannot be obtained by the IMO member institutions, every university does provide a local student career support page, and each one of them has a significant quantity and quality of employers, together with government support systems.

It's worth mentioning that it would be appropriate and useful to somehow share all these resources together by means of a single platform whereby, for example, by clicking the button "career support" on the page of a concrete university, a student or graduate would automatically be transferred to the unified page of IMO-member universities where the information about vacancies for maritime students is deployed.

On the one hand, he/she can choose the appropriate organisation and management level corresponding to his/her career, experience, qualification, salary, and location (region/country). On the other hand, the vacancy information for these so-called "international students/graduates" will be posted by partner organisations of IMO member institutions and stakeholders with an eye to filter the students' competence, education, specialisation, language abilities, etc., and send an invitation for the announced vacancy.

The digital platform will be placed for the researchers from the universities of IMO member countries, who will use it to conduct research - by making a search of information by region, country, speciality, gender, and so on - and afterwards, for further development, they can provide strategic recommendations and suggestions to the leadership of their government authorities.

To conduct such research is normally very time-consuming and inefficient, since it is practically impossible to interview more than 10th thousands of persons at once. Our proposed platform will involve more the 100 000 students, graduate professional workers, and academic and administrative personnel from all IMO member universities. A worldwide job centralising platform will be usable by IAMU students, employers, and other stakeholders, which could have huge potential by linking employers in the maritime sector with competent candidates from among IAMU member HEIs.

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ABSTRACTS

Avoiding Sea Blindness in the Context of Maritime Supremacy

Arda Özkan[1*], Levent Kırval[1]

[1] İstanbul Technical University, Faculty of Maritime, Department of Basic Sciences, İstanbul, Turkey

* Corresponding author: ardaozkan83@hotmail.com

Abstract. Since seas play an important role in the development and progress of countries, nations with access to the seas have engaged in global trade and enjoyed a better position for economic development. However, seas are being used more intensively than ever before, which also increases the pressure on the marine environment. The globalization of trade and the challenges faced in the worldwide transportation of goods have broadened the scope of strategies pursued at sea.

Along with these, the importance of the seas has not been sufficiently understood and researched by some states, a situation referred to in the literature as "Sea Blindness." The concept of sea blindness can be defined as the public, policymakers, administrators, academics, and scientists not knowing or appreciating the importance of the marine environment. Considering that most of the products we buy today reach us through maritime trade, it is essential that we address sea blindness for such a massive industry. In this context, maritime supremacy of states is important as long as it is used in accordance with national interests.

Maritime supremacy includes three elements: maritime economics, sea power, and scientific marine research. Sea blindness, on the other hand, is relevant for states that view the advantages afforded by their geopolitical positions and military interests as maritime supremacy. This situation constitutes only the sea power of maritime supremacy. The other two elements, maritime economics and scientific marine, encompass activities in areas such as the marine insurance, fishing activities, marine environmental protection, and seafarers, etc.

A strong military navy, a commercial navy that enriches the state, and scientific research significantly increase the power of states. In this context, there is a need to establish a maritime supremacy strategy to avoid sea blindness in foreign policy.

Keywords: Maritime security, maritime economics, sea power, scientific marine research.