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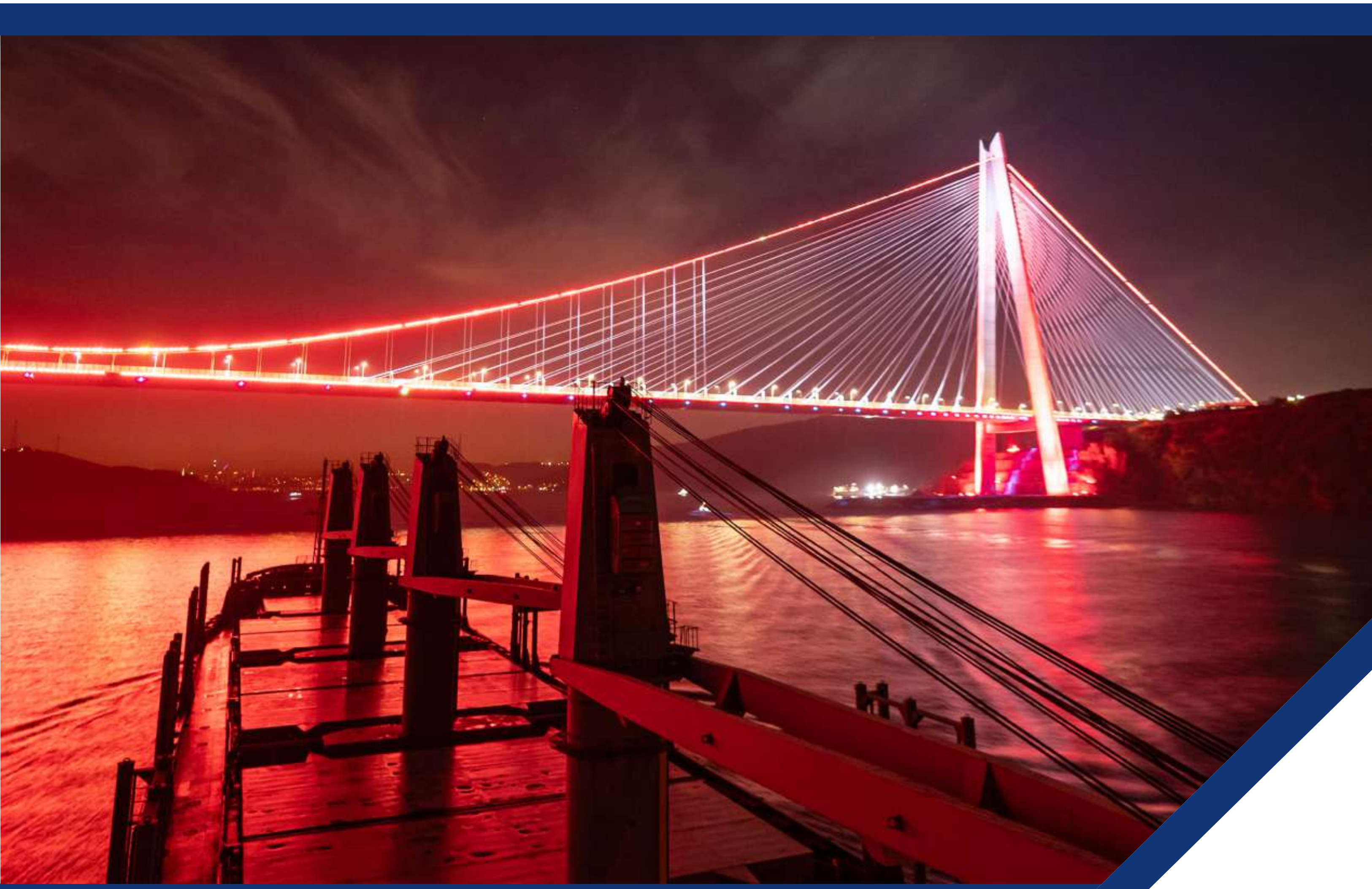

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Journal of ETA Maritime Science 2025;13(1):1

Selçuk Nas

Dokuz Eylül University Maritime Faculty, Department of Maritime Education and Training, İzmir, Türkiye

Today, the maritime industry is undergoing significant transformations in terms of sustainability, safety, and operational efficiency. Technological advancements and scientific research aim to reduce the environmental impact of maritime activities and enhance operational security. In this context, the presented studies in this Issue comprehensively address current challenges and possible solutions in the industry.

For example in this issue, studies on breakwater designs, both experimental and numerical, aim to make port and coastal structures more efficient. Research on permeable caisson breakwaters provides crucial findings on wave permeability and structural efficiency. Hydrodynamic analyses play a critical role in reducing wave loads and increasing port safety.

Similarly, the advantages and disadvantages of electric tugboats represent a significant step towards reducing the carbon footprint in the maritime industry. While electric tugboats offer benefits such as lower greenhouse gas emissions and reduced operating costs, they also bring challenges such as high initial investment costs and infrastructure requirements. This situation necessitates strategic planning by policymakers and industry representatives.

Additionally, studies on fuel and oil separator failures contain critical findings aimed at improving the operational efficiency of marine vessels. Analyses using the Fuzzy DEMATEL method highlight the negative impacts of maintenance deficiencies and mechanical failures on ship machinery, emphasizing the importance of preventive maintenance strategies.

Risk assessment studies on ship bunkering operations provide key insights into enhancing safety in the maritime industry Analyses conducted using the rule-based fuzzy FFMEA method reveal that incorrect valve operations and inadequate control mechanisms are among the most critical risks. These findings can serve as a basis for significant regulatory measures for both regulatory bodies and industry stakeholders.

The maritime industry is progressing towards a safer, more efficient, and sustainable future with the data obtained from such scientific studies. Supporting technological innovations and strengthening strategic planning will increase the industry's global competitiveness. Therefore, enhancing academic research and industry collaborations will ensure that the maritime industry achieves its sustainable development goals.

I am pleased to introduce JEMS issue 13 (1) consisting of the above important topics to our valued readers. I express my gratitude to the section editors, the editorial board, the writers who meticulously adhered to our publication guidelines to produce pieces of the highest caliber, and the reviewers whose perceptive research was approved for inclusion in this issue.

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Experimental and Numerical Study on the Hydrodynamic Efficiency of Permeable Caissons Barriers

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Abstract

Breakwaters are constructed to protect beaches and ports from high storms and waves. By bringing calm to the port, breakwaters also increase ship safety and operation. This paper presents a study of the breakwater partially submerged in water, consisting of precast concrete caissons suspended on a spaced pile, experimentally and numerically, to assess the efficacy of hydrodynamics. A set of scenarios were simulated for the proposed breakwater using FLOW-3D numerical modeling. It turned out that the coefficient of wave transmission (K_t) increases with relative barrier draft and decreases with relative breakwater width. When the waves impacting breakwater are relatively short, their effectiveness rises. As the seafloor slope increases, k_t decreases. The suggested breakwater disperses the waves and reduces the wave speed behind it. The wave velocities and vortices surrounding the breakwater decrease as the wave period (T) increases. In front of the barrier and at the wave crest, hydrodynamic pressure is at its peak. The numerically simulated results using FLOW-3D program are consistent with the experimental results.

Keywords: Breakwater, Coastal, Caissons, FLOW-3D, Pile system, Waves, Numerical model

1. Introduction

The coastal region of countries is one of the important vital areas. The coastal area and the port have an important impact on national income, as they have an important role in promoting the development of urban areas and increasing and revitalizing coastal tourism [1-6]. Despite all this, natural phenomena negatively affect the beaches, such as tides, waves, and sea currents [7-10]. A breakwater provides a calm area for waves, greatly reducing wave energy so that ships can anchor safely and assisting in construction and mineral and oil exploration [11,12]. Traditional barriers such as rubble mounds and gravity barriers are used to reduce the negative effects of waves and to create a safe and calm marine area [13-15]. Furthermore, these breakwaters hinder littoral drift, which causes notable erosion or accretion [16,17]. In recreational ports, part of the waves are allowed to pass so that tourists are not exposed to danger or any inconvenience and provide a stunning view of the beach [18-21]. Many investigations have been carried out on barriers and the effect of their hydrodynamic properties on wave reduction, using a set of numerical and experimental models to evaluate hydrodynamic performance [22-30]. The hydrodynamic properties of the fixed floating barrier were investigated for waves [31,32]. Although a closed wall structure for barriers can successfully reduce wave disturbance to the harbor's waters, its restricted water exchange capacity can degrade the water quality of the harbor. Furthermore, sediment siltation may be exacerbated by decreased harbor flow velocities. Thus, in recent years, researchers have focused on permeable breakwaters. Horizontal perforated barriers, a sequence of vertical cylinders, slotted and porous barriers are examples of structures that enhancing port flow speed and environmental sustainability by facilitating water exchange and efficient wave dissipation [33,34]. A caisson barrier that used the staggered arrangement of wave chambers to decrease the wave energy and had perforations on both the front and back walls [35]. The transmission and reflection properties of regular waves through thin, perforated walls were studied [36]. The effectiveness of pile-supported barrier caisson has been studied [37-39]. This paper aims to assess the

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hydrodynamic efficacy of a partially submerged breakwater by conducting an experimental and numerical investigation of precast concrete caissons supported on spaced piles.

1.1. Advantages of Permeable Caisson Barriers

This type of breakwater is commonly used for the following purposes:

- It is used as a common solution in deep water conditions.
- It is used in soils with low bearing capacity.
- Effectively used in wave energy applications.
- Providing continuous refreshing water in the coastal region, which reduces pollution.
- It doesn't occupy a lot of space, therefore having no effect on seafloor living organisms.

1.2. Research Objectives

- Proposing efficient, economical breakwaters to protect beaches.
- Assessing experimentally and numerically the hydrodynamic performance of the proposed barrier.

2. Materials and Methods

2.1. Experimental Work

In this study, a wave flume length of 15.6 m in length, 45 cm in height, and 30 cm in width was used, which is split into three sections. These sections are the wave generator section and the wave absorber section, which are both connected to the testing part of the flume. The length of the working part is 12 m. Figure 1 shows the dimensions and details of the flume. The vertical sides are composed of 1.2 cm thick glass. Using various wave characteristics, the experiments were conducted to assess the hydrodynamic performance. The barrier was a caisson that was held up by a system of large, spaced piles. To provide the required wave periods, the wave generator's velocity was adjusted. To measure the wave height (H_t), a digital ultrasonic water surface measuring device was used. The details of barriers a caisson as shown in Figures 2 and 3. Table 1 contains a summary of the experimental parameters.

2.2. Hydrodynamic Parameter

Two parameters are used to evaluate hydrodynamic performance. The reflection coefficient (K_r), which measures how much energy the barrier reflects, is the first parameter and may be calculated as follows [40]:

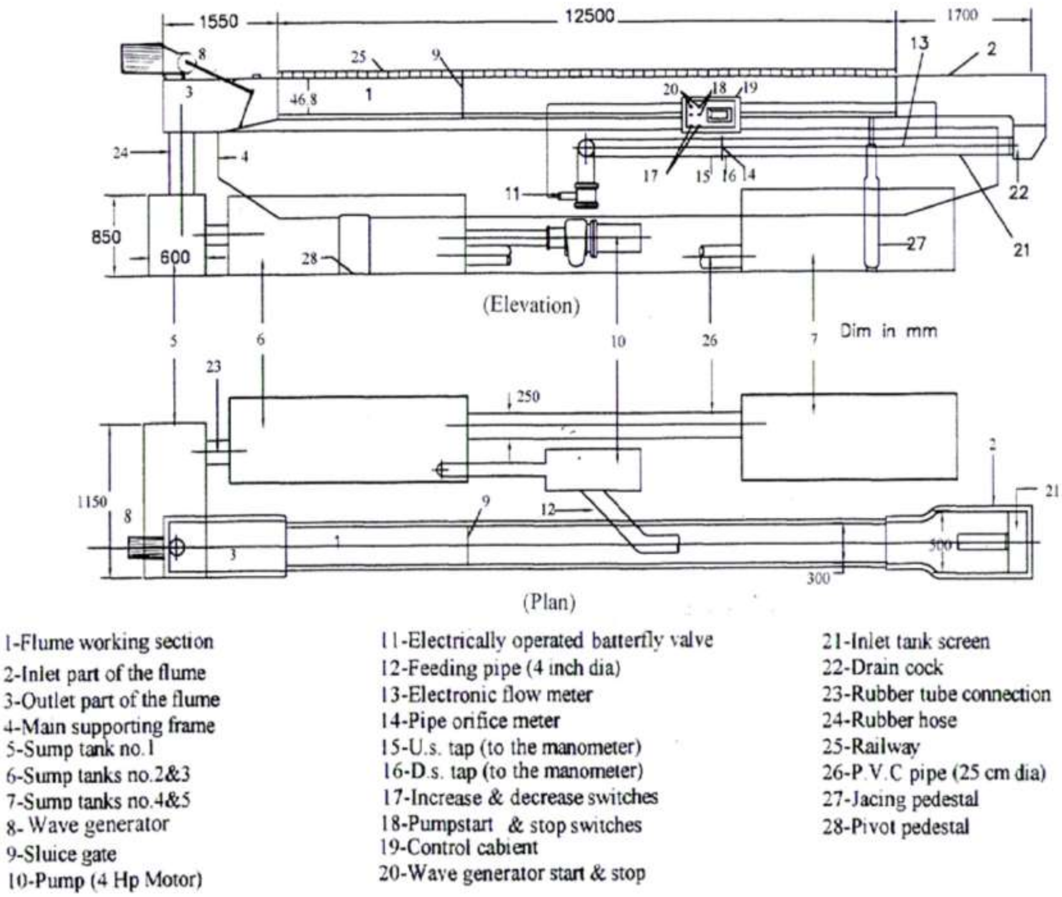

Figure 1. *Details of the wave flume*

$$K_r = \frac{H_r}{H_i} \quad (1)$$

Where: H_r is the height of the reflected wave, and H_i is height of the incident wave.

The second parameter is the height of the wave reflected by the incident wave, or the wave transmission coefficient (K_t), which can be calculated as follows [41]:

$$K_t = \frac{H_t}{H_i} \quad (2)$$

Where: H_t is the height of the transmitted wave.

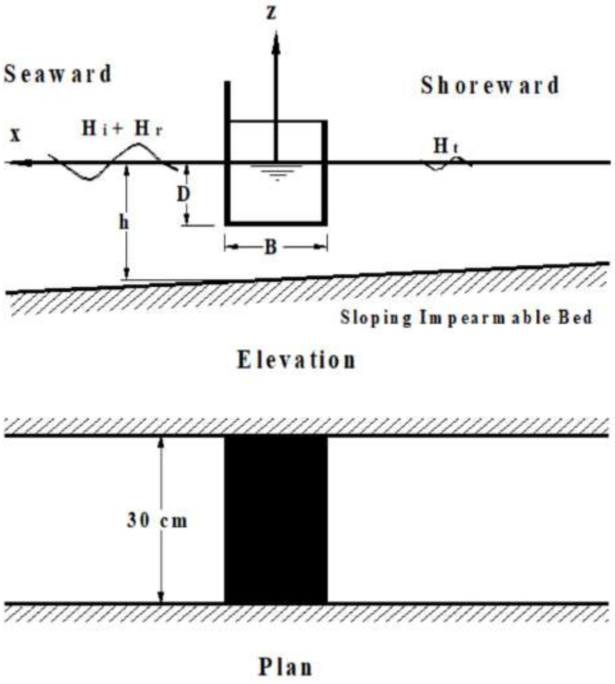

Figure 2. *Specifications of the pile system supporting the caisson on the solid bed*

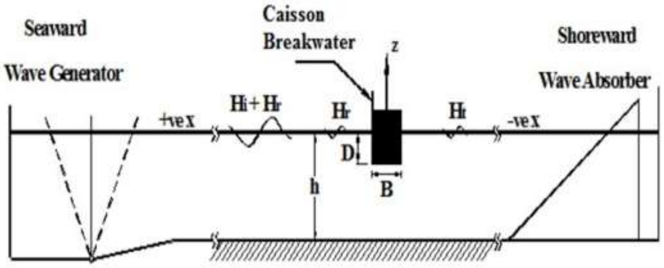

Figure 3. *Definition sketch for breakwater model*

Table 1. *Experimental parameters of the suggested model*

Parameter	Range of water levels
Depth of water (h)	20 (cm)
Width of barrier (B)	1, 20, 35, 50 and 65 (cm)
Wave length (L)	70-510 (cm)
Draft of barrier (D)	0, 6, 10, 14 and 18 (cm)
Bed slope (S_b)	0%, 2% and 4%

2.3. Numerical Simulations

The proposed barrier was numerically simulated FLOW-3D program. The hydrodynamic performance of the curtain vertical breakwater supported on piles was examined in this study using the computational fluid dynamics (CFD) methodology. The CFD uses computer-based simulation to analyze systems that involve fluid flow-related phenomena, including the motion of water waves. This method is quite effective and has many different engineering application areas. CFD can provide a faster and more economical solution than physical modeling [42]. Numerous applications are made possible by the suggested program's development base. The program's coding is based on finite volume theory, and the 3D Reynolds mean was calculated using Navier-Stokes (RANS) calculations [43]. In addition to traditional linear waves, FLOW-3D can simulate irregular and nonlinear waves [44]. The flow zones are separated into a grid of rectangular cells of varying sizes. Values for the fundamental flow quantities (such as velocity, pressure, and density) are kept for every cell [45-47]. The Fractional Area Volume Obstacle Representation (FAVOR) approach was used in the software to arrange the breakwaters system in the grids [48]. Figure 4 illustrates the numerical simulation process.

3. Results and Discussions

3.1. Experimental and Numerical Results

The experimental and numerical transmission coefficient results at B/h=1.5 were compared as shown in Figure 5. As Figure 5a illustrates, the experimental results at number of

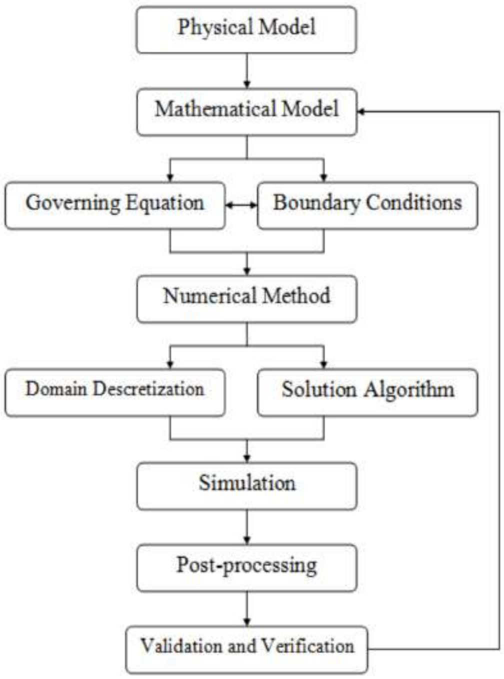

Figure 4. *Process for numerical simulation*

waves K_h=1.9 are consistent with the simulated values. It is also noted that as the draft increases, k_t decreases when D/h=0.4 is K_t=0.20, and when D/h=0.6 is K_t=0.10. The explanation for this is that the passage of water under the barrier decreases, and thus the dissipation of wave energy increases. Also, the width of the barrier increases the path of the waves below it, and thus the energy of the waves decreases. Furthermore, at number of waves (K_h)=1.06, the numerical model reduces k_t by roughly 7%, as shown in Figure 5b. In Figure 5b compared to Figure 5a, it is clear that k_t increases with the decrease in k_h, in Figure 5a at draft=0.2, water depth was 0.4 while in Figure 5b, at draft=0.2, the water depth was 0.7. Also, as in Figure 5a, it is noted that the values of k_t decrease with the increase in the values of the draft, but the agreement of the experimental results with the numerical results is not as accurate as the results when the wave number was equal to 1.9. Which indicates that increasing the wavenumber (i.e. increasing the number of waves per second) gives better compatibility results. Figure 5c illustrates the consistency among the experimental and numerical model results for K_h=0.75. The experimental and numerical K_t results at K_h=1. 9, 1.06, 0.75, and 0.4 when B/h=0.5 were compared in Figure 6. The results of experimental and numerical for various values of k_h showed that there was agreement between them, as seen in Figures 6a and 6b. Nevertheless, as Figures 6c and 6d demonstrate, numerical exceeds K_t from 7 to 13% for K_h less than 1.06 at D/h less than 0.6 at this point, so the numerical model is most accurate. The experimental and numerical K_t and K_r results at various D/h when B/h=0.5 is shown in Figure 7. For transmission coefficient, Figure 7 demonstrated that, for K_h values less than 0.8, the experimental results accord with the numerical results; however, for K_h values more than 0.8, the

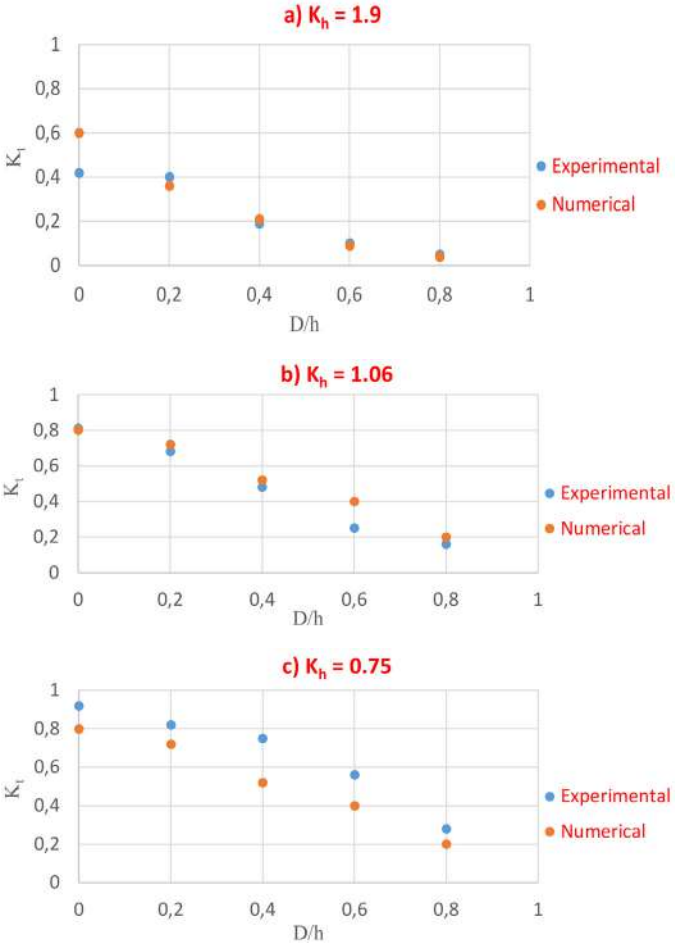

Figure 5. *Comparison of experimental and numerical K_t results at B/h=1.5*

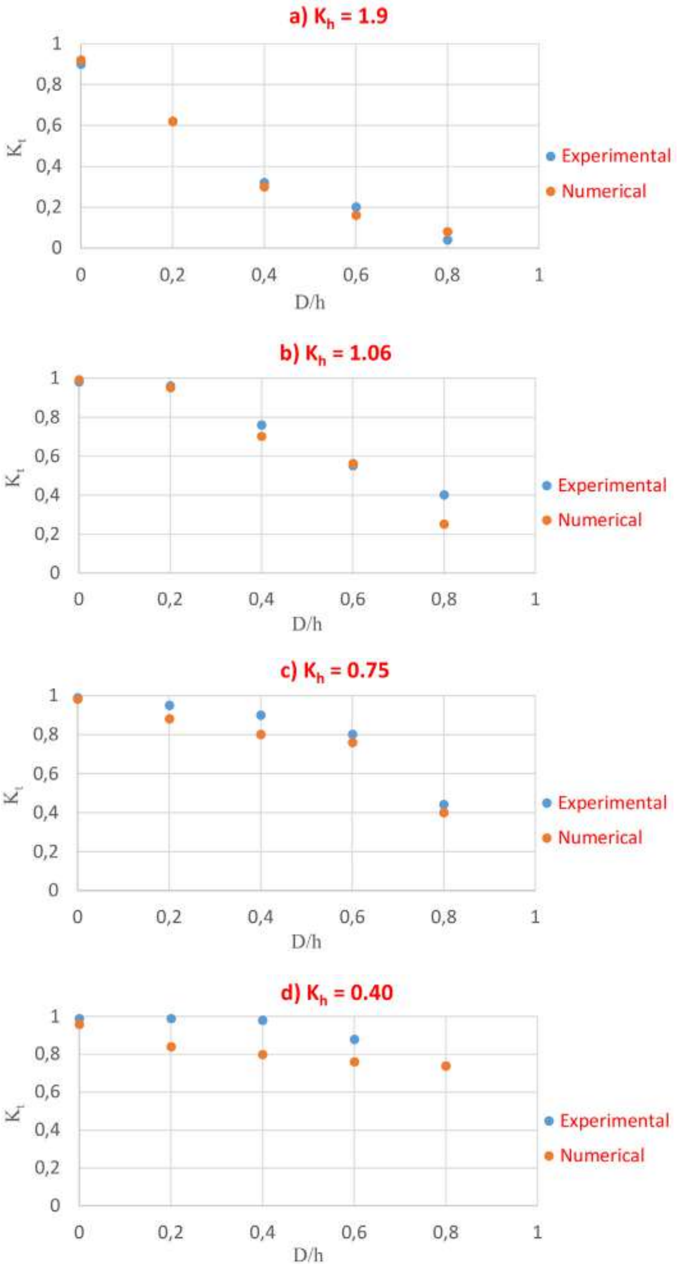

Figure 6. *Comparison of experimental and numerical K_t and K_r results at B/h=0.5*

transmission coefficient is exceeded by the numerical model by around 8 to 24%. Furthermore, Figure 7 demonstrates that for reflection coefficient, the numerical and experimental results agree when K_h is greater than 2.0, but when K_h is less than 2.0, the numerical model exceeds reflection coefficient by roughly 8-13%.

Figure 8 demonstrates a comparison between present study (experimental results) and various other similar studies for B/h=0.5 at D/h=0.30 and 0.60. The results showed that k_t values for this study are lower than those for previous studies under the same conditions. Figure 9 demonstrates the relationship between the numerical (K_t, K_r) and the wave number at different D/h at B/h=1.0 for experimental results. As K_h and D/h increase, K_t decreases, as seen in Figure 9a. However, Figure 9b shows that as K_h and D/h increase, the numerical K_r also rises.

3.2. The Impact of the Bed Slopes (S_b) on Hydrodynamic Performance

The relationship between B/h and K_t is shown in Figure 10 for S_b at K_h=1.88 and D/h=0.0, 0.2, 0.4, 0.6, and 0.8 for experimental results. The figure demonstrates that when B/h increases, K_t reduces for all bed slopes. Also, K_t decreases with increasing S_b. The breakwater was very efficient in reducing wave energy. This happens because of friction between the waves' transferred energy and the surface of breakwater, which causes more wave energy to be lost through the barrier. In addition to the vortices at the barrier's bottom end shedding during transmission. Moreover, Figure 8 demonstrates that kt reduces as D/h rises.

3.3. Hydrodynamic Pressure Distribution, Wave Velocities, and Vortex Formation Around Suggested Breakwater

Figure 11 illustrates the hydrodynamic pressure distribution caused by wave movement on the breakwater. The

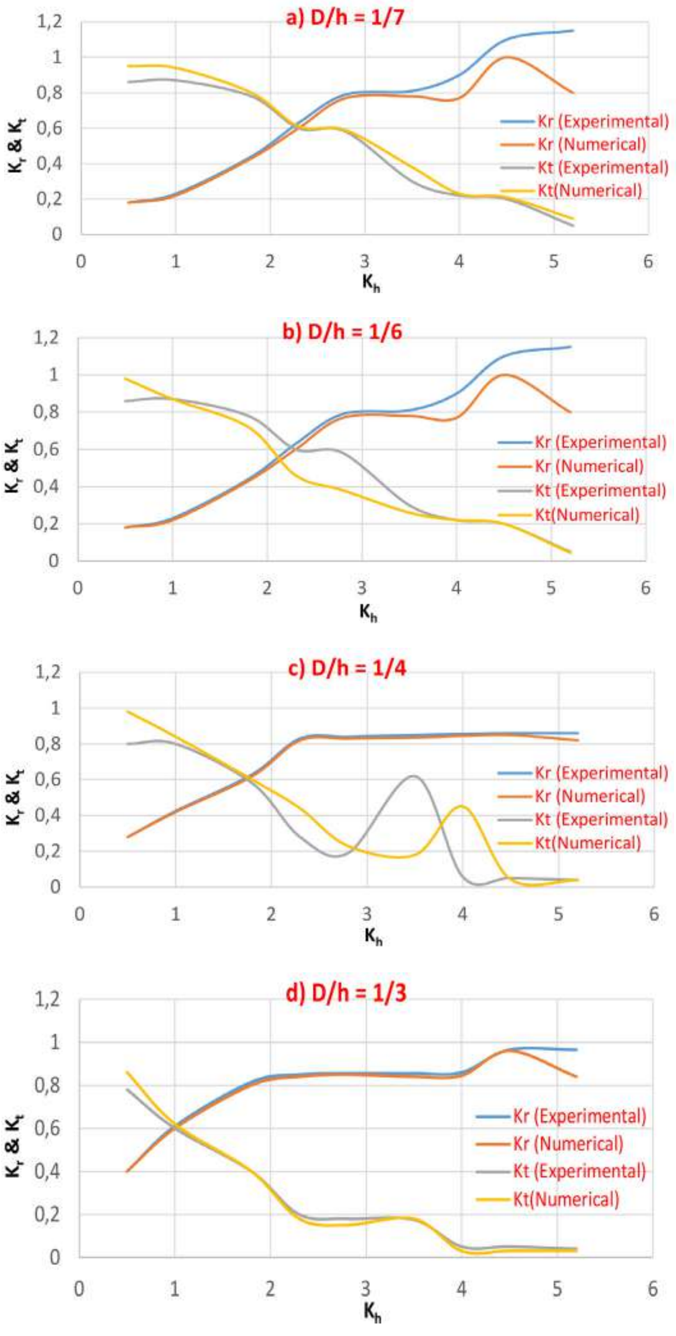

Figure 7. Comparison between Kr and Kt for different relative drafts at B/h=0.5

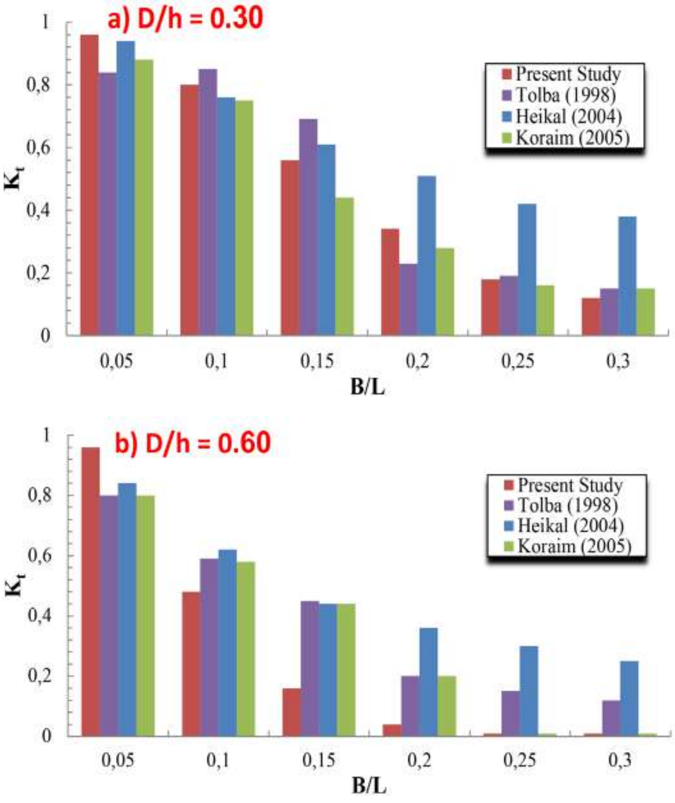

Figure 8. A comparison between K_t of this study and various previous studies

hydrodynamic pressure was strongest in front of the breakwater and close to the wave crest. The wave vortices surrounding the suggested breakwaters at various wave periods are seen in Figure 12. It was found that shorter wave periods also resulted in shorter wave lengths, which increased the number of vortices surrounding the breakwater. Hence, for T=1.1 s, the vortices in Figure 12b were larger than those in Figure 12a for T=1.3 s. It shows that the vortices surrounding the barrier expand as the wave period shortens. Figure 13 illustrates the wave velocities surrounding the barriers at various wave periods. It is evident from the figures that higher velocity was experienced around the barrier during shorter wave periods due to shorter wave lengths. The wave velocity rises surrounding the barrier as the wave period reduces, as shown in Figures 13a-c for T=0.8, 1.1, and 1.3 s, respectively.

4. Conclusion

These conclusions were drawn after analyzing the results as follows:

The transmission coefficient reduces with rising relative barrier width but rises when the barrier draft increases.

The transmission coefficient reduces as the seafloor slope rises.

The proposed breakwater scatters the waves through it and reduces the speed of the waves behind it.

The hydrodynamic efficiency of the barrier may be predicted using the suggested numerical model.

The hydrodynamic pressure and velocity field surrounding the barrier can be determined by the utilization of the numerical model.

The highest value of hydrodynamic pressure is at the wave crest and in front of the breakwater.

The simulated results using FLOW-3D program are consistent with the experimental results.

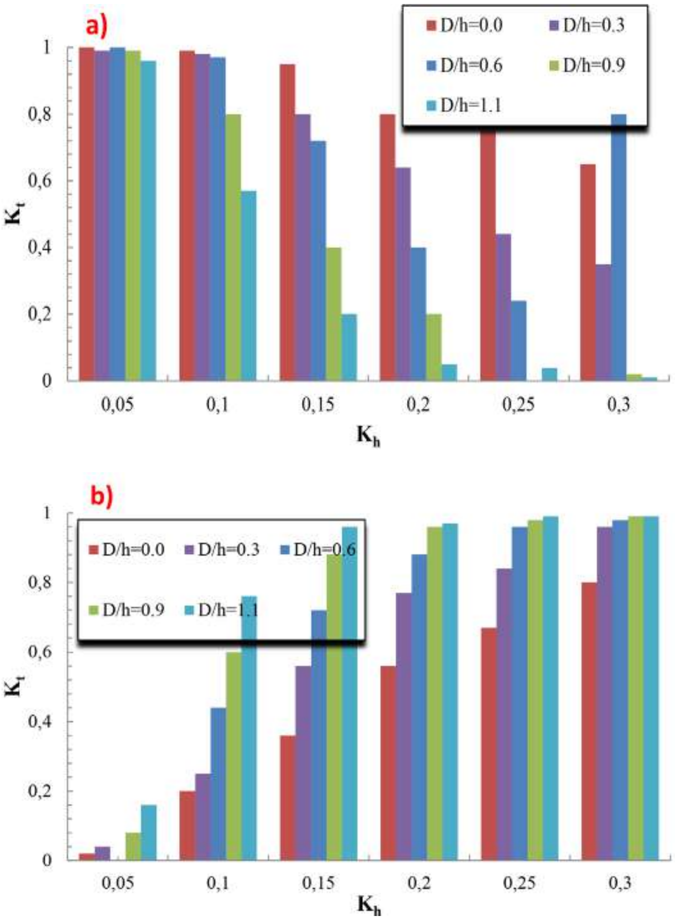

Figure 9. K_t and K_r versus K_h at B/h=1.0

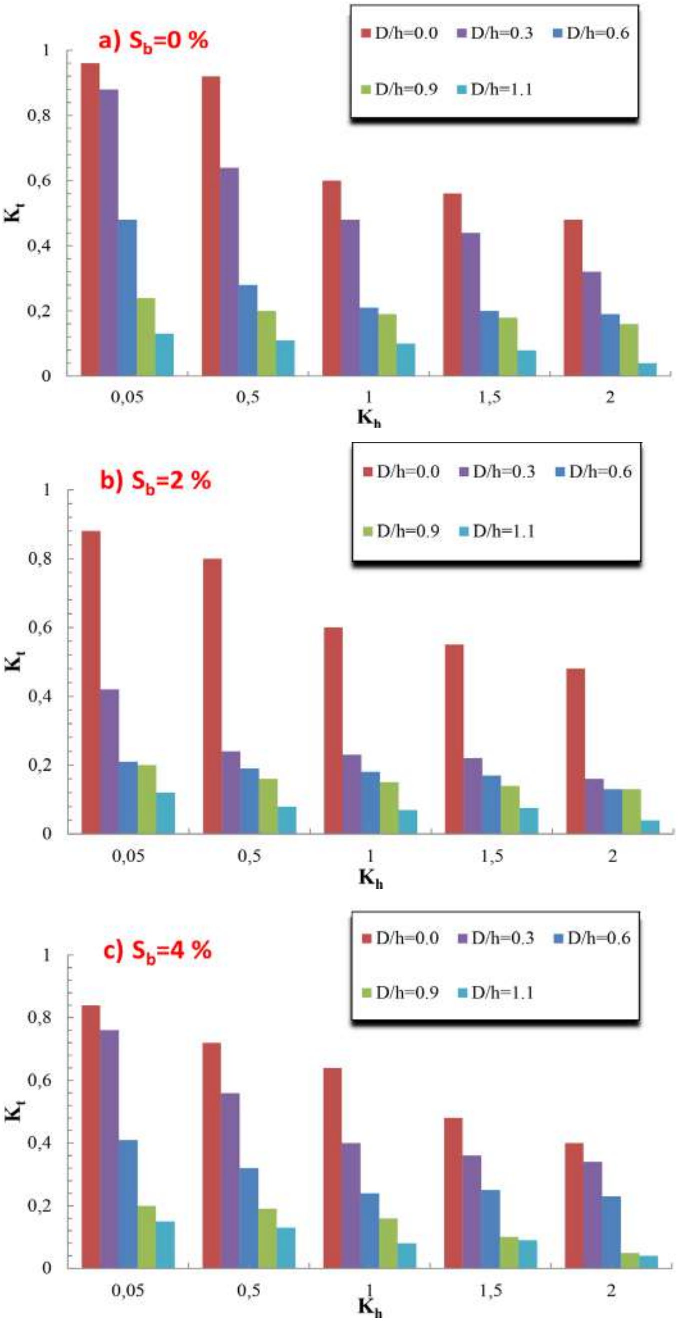

Figure 10. K_t versus K_h for different D/h at S_b=0.0%, 2%, and 4%

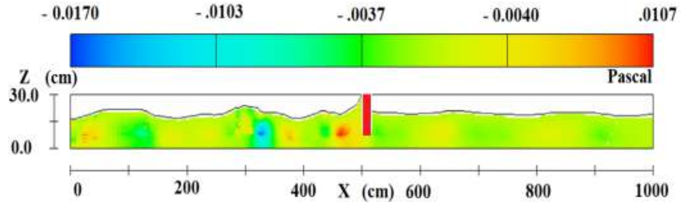

***Figure 11**. Hydrodynamic pressure distribution surrounding the barrier*

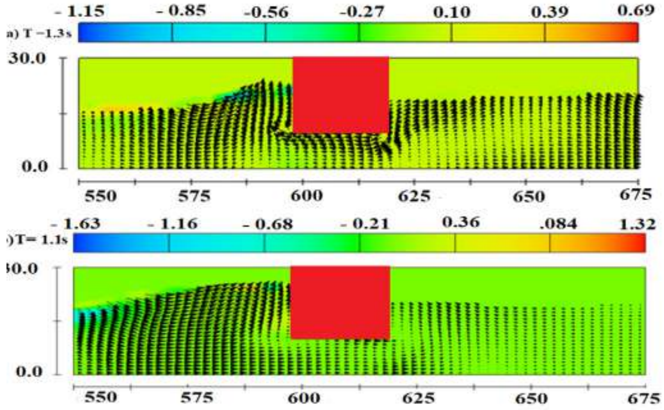

***Figure 12**. Distribution of wave vortices*

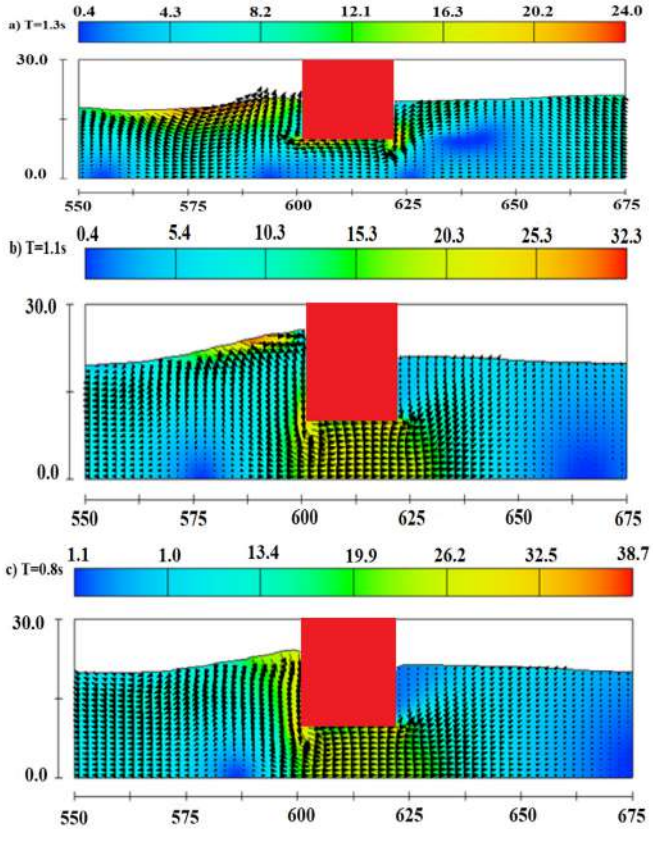

***Figure 13**. Distribution of wave velocities*

Footnotes

Authorship Contributions

Concept design: K. B. Hussein, M. Ibrahim, and S. H. Abd El Ghany, Data Collection or Processing: K. B. Hussein, M. Ibrahim, and S. H. Abd El Ghany, Analysis or Interpretation: K. B. Hussein, M. Ibrahim, and S. H. Abd El Ghany, Literature Review: K. B. Hussein, and M. Ibrahim, Writing, Reviewing and Editing: K. B. Hussein, and S. H. Abd El Ghany.

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Ship Bunkering Operations Risk Assessment using Rule-Based Fuzzy Failure Mode Effect Analysis (FFMEA)

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Abstract

Ship bunkering operations play a critical role in sustaining maritime transportation; however, they also entail significant risks to the environment, vessels, and crew. This study conducts a comprehensive quantitative risk assessment of bunkering operations using the rule-based fuzzy failure mode and effect analysis method. A total of 27 critical failure modes were identified, and expert evaluations were performed for the severity, frequency, and detectability of each failure mode. These evaluations are processed through fuzzy membership functions, an inference engine, and a set of 125 rules to calculate the fuzzy risk priority numbers (FRPNs) for each failure scenario. The analysis results indicate that the three most risky failure modes, as measured by their FRPN scores, are FM19 - Lack of proper control mechanisms (7.04), FM18 - Incorrect valve operations (6.93), and FM14 - Ineffective communication between ship crew and shore or barge personnel (6.92). The findings of this study present practical recommendations regarding critical failure modes, with notable implications for improving regulatory compliance, strengthening operational safety, and reducing maritime risks. These outcomes highlight the necessity of systematic risk assessment approaches to guide decision-making and promote safer, more sustainable bunkering operations.

Keywords: Ship bunkering, marine engineering, FMEA, Risk analysis, Fuzzy logic, FRPN

1. Introduction

The maritime industry is a fundamental component of global trade and facilitates the transport of goods across the world's vast oceans [1]. Within this extensive sector, ship bunkering operations play a role by supplying fuel for maintaining the operational continuity of maritime vessels [2]. Despite its critical importance, ship bunkering is a multifaceted process involving a network of interconnected systems and procedures, each with its own risks and challenges. Consequently, careful attention is required to ensure both safety and efficiency throughout the operation.

The inherent dynamic nature of ship bunkering operations introduces significant risks. The process involves not only the transfer of fuel but also the coordination of various systems on the ship, barge, and at port. This complexity increases the likelihood of accidents and operational failures. In addition, the frequency of bunkering operations amplifies these risks. Each operation requires the seamless functioning of human and mechanical elements to prevent incidents.

Bunkering is particularly hazardous because of the potential for leaks and spills, which can have severe environmental and health impacts [3]. Although stringent safety protocols are in place, even minor incidents can escalate into major disasters, affecting marine environments and posing serious risks to life [4]. The routine nature of bunkering operations does not diminish the associated risks, which include potential accidents and environmental damage from spills. The impact of bunker spills is twofold: they can disrupt marine ecosystems through persistent oil pollution and lead to legal and financial consequences for involved parties, such as crew members and shipowners [5]. It is important to acknowledge that oil spills are not limited to oil or oil products transported as cargo; any vessel can potentially contribute to an oil spill incident due to bunker oil stored within its tanks [6]. Most oil pollution claims are related to

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bunker fuel rather than cargo oil, with many spills occurring during bunkering [4,7]. Furthermore, bunkering operations involve a broad range of risks beyond leaks, including potential injury to crew members and equipment damage. Thus, these operations require thorough preparation, strategic planning, and meticulous attention before, during, and after. Given the critical nature of bunkering, conducting a comprehensive risk analysis and implementing effective precautions are essential for mitigating risks and preventing accidents. This forward-looking strategy plays a critical role in maintaining operational safety while simultaneously optimizing efficiency and minimizing risks.

2. Literature Review

The maritime industry is inherently complex and dynamic, with high levels of risk. To effectively prevent accidents, risk analysis is critical. In high-risk sectors, such as maritime ones, it is essential to analyze risks and implement preventive measures. Consequently, risk analysis has become a fundamental aspect of the marine industry and is one of the most frequently studied and researched topics in recent years [8]. Through risk analysis, both existing hazards and potential future dangers can be identified, allowing effective preventive measures to be developed. This process is vital for improving the safety of maritime operations and reducing the risk of accidents.

Given the inherent risks and complex nature of maritime operations, various risk assessment methodologies have been developed to mitigate these risks. Methods such as fault tree analysis (FTA) [9], failure mode and effects analysis (FMEA) [10], event tree analysis [11], formal safety assessment [12], human error identification and reduction technique [13], Bow-Tie analysis [14], hazard and operability [15], Bayesian network (BN) [16], functional resonance analysis method [17], analytic hierarchy process (AHP) [18], and analytic network process [19], have been employed to evaluate and manage risks. FMEA, in particular, is a well-established tool used to identify and prioritize potential failure modes within systems and operations.Hybrid FMEA methodologies have emerged as a robust approach for addressing complex risk scenarios in various high-risk industries. These methods integrate traditional failure analysis techniques with advanced computational tools to enhance decision-making under uncertainty. For example, fuzzy logic and machine learning-based FMEA approaches have been successfully utilized in healthcare to prioritize patient safety risks [20]. In aviation, BN have been combined with FMEA to improve fault detection/detectability (D) and analyze critical component failures [21]. Similarly, in the energy sector, a fuzzy-AHP hybrid approach has been applied to evaluate risks in renewable energy projects and address sustainability challenges [22]. In manufacturing, genetic algorithm-based FMEA has been adopted to optimize production processes and minimize downtime [23]. Additionally, Dinmohammadi and Shafiee [24] proposed a fuzzy-FMEA framework specifically for offshore wind turbines and demonstrated its effectiveness in evaluating operational and maintenance risks. These advancements demonstrate the potential of hybrid FMEA methodologies to address the unique challenges of maritime operations, particularly in high-stakes scenarios like ship bunkering. Various fuels, including heavy fuel oil (HFO) and marine diesel oil (MDO), power ships. However, one of the primary concerns in the maritime industry is the environmental impact of ship operations, particularly the emissions generated by ships. The International Maritime Organization (IMO) has enforced rules to reduce these emissions, which include restrictions on sulfur oxide (SO_x) and nitrogen oxide (NO_x). To comply with these regulations and reduce their environmental footprint, ship operators are exploring emission-lowering technologies, such as selective catalytic reduction, scrubbers, exhaust gas recirculation, and alternative marine fuels. According to the literature, vital marine alternative fuels are liquefied natural gas (LNG), ammonia, hydrogen, ethanol, dimethyl ether, methanol, and biodiesels [25-27]. The fuel choice depends on cost, availability, and environmental considerations. Recently, there has been a growing concern about using alternative fuels such as LNG to reduce emissions and comply with environmental regulations. A review of studies on ship bunkering operations revealed a substantial body of research, with a particular emphasis on studies focused on LNG [28-35]. However, using alternative fuels presents challenges, including safety concerns and infrastructure requirements. Although alternative fuels are considered viable options for future utilization, most ships continue to use HFO and MDO fuels. Despite this fact, the extant literature on HFO and MDO, which are the fuels utilized by current vessels, exhibits a scarcity of risk analysis studies. The existing literature predominantly examines management techniques for bunkering operations, with a particular emphasis on optimizing costs, selecting appropriate ports, determining ship routes, and establishing contracts to mitigate fuel-related expenses [36-38].

The limited body of literature primarily concentrates on performing risk analyses for ship bunkering operations with the objective of reducing the risk of potential accidents. Akyuz et al. [4] addressed bunkering risks from the perspective of human factors. Their study focused on predicting human errors during bunkering operations through a case study of a chemical tanker platform. They employed the shipboard operation human reliability analysis method to analyze these risks. Their research provides recommendations for reducing human errors in the bunkering process. Kamal and Kutay [5] analyzed the causal mechanisms underlying oil pollution during bunkering by using a fuzzy BN (FBN) approach with 16 root nodes. Industry experts with extensive experience identified the causal factors in their model, enabling the establishment of probabilistic relationships among these factors. The results provided solutions for regulatory authorities, and shipowners could use the findings to mitigate the risk of oil pollution associated with bunkering operations. In another study, Çiçek and Topcu [39] introduced a risk-based decision-making framework to enhance the management of operational and managerial processes in ship fleet management. FTA and evidential reasoning methods were used to analyze failures. To address the lack of information and uncertainty inherent in these processes, the model incorporated fuzzy logic. Their model was specifically applied to bunkering, one of the most critical shipboard operations: bunkering. The results demonstrated that the proposed model can produce solutions to mitigate ship bunkering risks [39]. Finally, Doganay et al. [40] performed a comprehensive risk analysis of bunkering operations, covering key stages such as the berthing and anchoring of the fuel barge, the fuel transfer process, the underthing of the fuel barge, and the voyage preparation phase. The authors utilized the conventional FMEA method, identifying nine failure modes during operation. Through their analysis, they calculated the risk priority numbers (RPN) for the identified hazards and determined the necessary precautions for each hazard. Following the implementation of these measures, they reassessed the risks and calculated the residual risk scores for each hazard. Additionally, they provided recommendations to ensure the operation was conducted safely and efficiently.

This study aims to perform a comprehensive risk assessment of ship bunkering operations using FMEA. Although the FMEA is widely used, it has some limitations, especially in terms of managing the uncertainties and dynamic complexities associated with maritime environments [41,42]. To address these issues, this study employs fuzzy FMEA (FFMEA), which integrates fuzzy logic into the FMEA framework. This integration enhances the FMEA's ability to handle uncertainties and provides a more nuanced analysis of the failure modes. By incorporating fuzzy logic, this study delivers a thorough and precise evaluation of the risks associated with ship bunkering operations. The application of FFMEA is particularly relevant given the frequent occurrence (O) and inherent risks of bunkering operations. Through an evaluation of 27 key failure modes, this study aims to identify potential vulnerabilities and offer actionable recommendations for risk mitigation. The findings are expected to significantly contribute to improving safety practices in ship bunkering operations and advancing overall risk management strategies in the maritime industry.

3. Methodology

This section covers the materials and methods used in the study. The primary material of the study was the ship fuel system, and the method employed was the rule-based FFMEA.

3.1. Ship Bunkering

Marine fuels play a pivotal role in the operation of ships, serving as the primary power source for key components such as main engines, generators, and boilers [43]. The ship fuel system refers to the complete structure that encompasses several processes, including bunkering, storage, transfer, cleaning, heating, and modification of parameters such as temperature, pressure, and viscosity of fuel [44].

The fuel system of a vessel is generally initiated at the bunker line, which is strategically located on the deck to facilitate the transfer of fuel from external sources. This line serves as the primary conduit for receiving fuel during bunkering operations and is designed to ensure efficient and secure handling of fuel, minimizing the risk of leaks and contamination. This line encompasses the interconnections, valves, sampling locations, and control points where fuel is pumped into the vessel. From this pipeline, fuel is conveyed to an appropriate storage tank within the system via valve operation. Once in the storage tank, the fuel is heated and allowed to settle before being sequentially transferred to the settling and service tanks. During this process, the fuel temperature is increased, and the fuel undergoes separation. Subsequently, the fuel, which has the temperature, pressure, and viscosity values in the desired range, is sent to the ship's engines for use.

HFO and MDO are two types of fuel commonly used by ships and are accepted as benchmarks [46]. Various fuel tanks and pipelines are used to accommodate these two types of fuel. Nevertheless, it is worth noting that the two lines may also intersect at locations where fuel changeover procedures take place. Figure 1 shows an example of a ship bunker and transfer system. The graphic illustrates fuel flow dynamics, where the brown indicators represent the HFO pathways, and the yellow indicators denote the MDO pathways.

3.2. FFMEA

FMEA is a rigorous methodology that is used in a variety of industries to examine safety and risks [47]. The efficiency of this approach in detecting and preventing possible faults has contributed to its increasing popularity [48,49]. FMEA has three fundamental elements, namely, severity (S), O, and D, which are used in the computation of a RPN. The determination of the RPN involves the multiplication of these factors, resulting in a quantitative assessment of

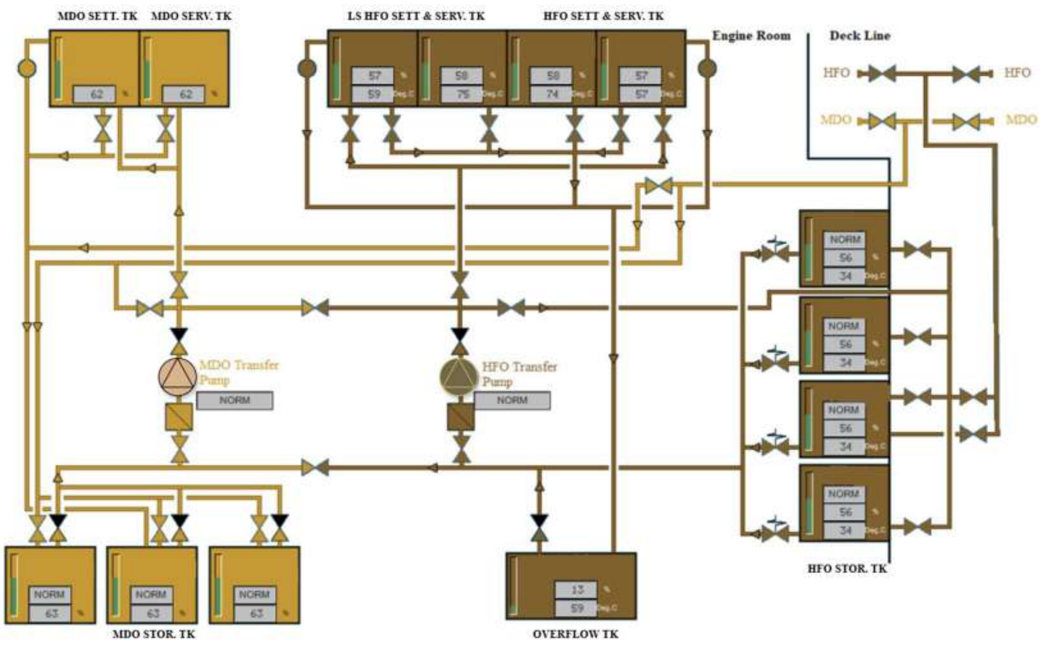


Figure 1. *Ship HFO-MDO bunker and transfer system [45]*

the risk associated with a certain failure mode [37]. The multiplication described below and given in Equation (1) forms the basis of FMEA.

$$RPN=O\times S\times D \quad (1)$$

The most commonly used rating system in the literature ranges from 1 to 10. The scale developed by Pillay and Wang [50], which is widely favored in academic literature, was used in this investigation. Tables 1-3 present this scale.

Despite the widespread use of FMEA methods, the use of risk scoring using multiplicative addition has been criticized by various authors in the literature [51,52]. The growing intricacy of the rapidly evolving environment has surpassed the constraints of conventional FMEA, resulting in the emergence of many hybrid models in recent scholarly works. The objective of these models is to improve the FMEA process and exploit its advantages [53]. The most popular method to improve FMEA is the fuzzy method [54]. Therefore, this work used fuzzy set theory to mitigate the limitations of RPN computation and improve the efficiency of the classical FMEA method. The methodological approach of the study is illustrated in Figure 2. The first step is to define the system. The failure modes of this study were then obtained from two primary data sets. The first section is a literature review; however, as mentioned in the introduction, risk analysis studies related to ship fuel bunkering are quite limited. Existing studies have identified only a small number of failure modes. Therefore, as a secondary data source, experts participating in the study were asked to identify the failure modes related to fuel bunkering. Once the failure

Table 1. *Scores for the probability of occurrence*

Score	Probability of occurrence	Possible failure rate
10	Very high	≥0.5
9	Very high	0.1
8	High	0.05
7	High	0.01
6	Medium	0.05
5	Medium	0.001
4	Medium	0.0005
3	Low	0.0001
2	Low	0.00005
1	Very low	≤0.00005

Table 2. *Scores for severity*

Score	Severity
10	Very high
9	Very high
8	High
7	High
6	Medium
5	Medium
4	Medium
3	Low
2	Low
1	Very low

modes were determined, the next step involved collecting expert scores. The fuzzy model with its inference engine and membership functions (MFs) was then established. After the fuzzification, inference engine, and fuzzification processes, the fuzzy RPN (FRPN) outputs were determined. The primary stages of the FFMEA process are described below.

Step 1. Define the system: Identify the system under consideration. The first step involves identifying the boundaries of the system, its components, and how they interact with each other and the external environment. Understanding the system is crucial for the subsequent steps in the FFMEA process.

2. Provide failure modes: Identify potential ways in which the system or its components can fail. This step involves brainstorming and analyzing data to identify possible failure modes.

Step 3. Get expert scores: Engage domain experts to assess the O, S, and D values of each failure mode. Experts provide their scores based on their knowledge and experience, which are crucial inputs for the FFMEA analysis.

Table 3. *Scores for probability of detection*

Score	Detectability	Detection probability (%)
10	Very high	0-5
9	Very high	6-15
8	High	16-25
7	High	26-35
6	Medium	36-45
5	Medium	46-55
4	Medium	56-65
3	Low	66-75
2	Low	76-85
1	Very low	86-100

Step 4. Construct the FFMEA model: The FFMEA model incorporates fuzzy logic to handle uncertainty and ambiguity in expert assessments. The model defines how the inputs (S, O, and D) are quizzified, processed through the rule base, and defuzzified to obtain the FRPN outputs.

Step 5. Define input MFs: Define MF for each input (S, O, D) to convert expert scores into fuzzy sets. These MF determine how each input value is mapped to a fuzzy set, capturing the linguistic variables used by the experts (e.g., “low,” “medium,” and “high”).

Step 6. Define output MFs: Similarly, define MF for the output (RPN) to convert aggregated fuzzy scores into a FRPN. The output MF define how the FRPN values are mapped to linguistic variables (e.g., “low,” “medium,” “high”).

Step 7. Define rule base and inference mechanism: Define rules governing how input fuzzy sets are combined to calculate the output FRPN. This involves defining the rule base (a set of if-then rules) and the inference mechanism (how the rules are applied to the input fuzzy sets).

Step 8. Obtain FRPN outputs: Apply the FFMEA model to the expert scores to obtain FRPN outputs for each failure mode. The FRPN values represent the prioritization of every possible failure mode, taking into account the uncertainties and expert judgments involved in the assessment.

4. Ship Bunkering Risk Evaluation

Ship bunkering risk assessment was carried out using the FFMEA framework. The subsequent sections encompass the risk analysis steps of the study.

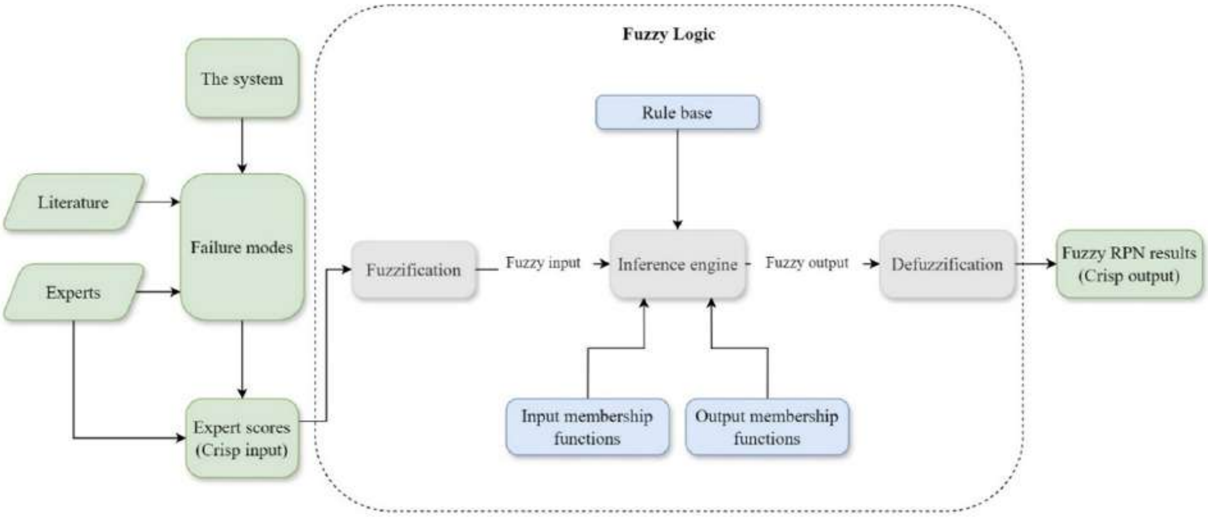


Figure 2. *Methodological framework of the study*

4.1. The System

The risk analysis system relates to bunkering operations for maritime vessels. The system consists of the following primary structural sections:

i. Failure modes concerning the vessel before berthing.

ii. Failure modes regarding the supplier before berthing.

iii. Failure modes related to preparations before transfer.

iv. Failure modes occurring during bunkering.

v. Failure modes pertaining to the completion of bunkering.

4.2. Failure Modes

The failure modes associated with bunkering have been recognized by marine engineering experts. The failure modes of the ship bunkering operations are illustrated in Table 4.

Table 4. *Failure modes*

Failure Mode	Definition of failure mode
FM01	Lack of knowledge or awareness about bunkering procedures
FM02	Improper bunkering procedures
FM03	Lack of familiarity with ship bunkering
FM04	Non-compliance with crew rest hour regulations
FM05	Inadequate planning and lack of pre-bunkering meetings
FM06	Blocked air vents in bunker tanks
FM07	Loose or improperly secured-sounding pipe caps
FM08	Malfunctioning low- and high-level alarms in bunker tanks
FM09	Non-operational bunker level monitoring systems
FM10	Incorrect tank-sounding measurements
FM11	Inadequate electrical insulation in bunker lines or supplier-to-ship connections
FM12	Deteriorated or damaged bunker hoses
FM13	Unsafe access between the ship and the supplier
FM14	Ineffective communication between the ship crew and the shore or barge personnel
FM15	Unplugged scuppers
FM16	Improperly designed or maintained bunker drip trays
FM17	Defective bunker manifold connections
FM18	Incorrect valve operation
FM19	Lack of proper control mechanisms
FM20	Absence of oil spill cleanup materials
FM21	Improper smoking bans
FM22	The presence of naked lights
FM23	Incorrect or substandard fuel supply
FM24	Material Safety Data Sheets for bunker fuel
FM25	Malfunctioning bunker supply line pressure and temperature gages
FM26	Improper bunker sampling procedures
FM27	Undrained bunker lines and hoses

4.3. Expert Profiles

The methodological foundation of this paper is a numerical risk analysis structure based on expert systems. Consequently, expert opinions are required at certain points of the method. Since this study aims to be highly specific in the field of ship bunkering operations, the experts were selected meticulously. The experts who participated in the study were carefully selected, taking into consideration the complex technical aspects of ship bunkering operations. The research team includes five experts. To enhance the reliability of the expert evaluation, a preference was given to experts with a minimum of 15 years of professional experience. Four of the professionals hold the post of chief engineer at a tanker shipping company that operates in the seas. One of the employees of the shipping company currently occupies the role of a marine engineering technical inspector. Information about the participating experts is presented in Table 5.

4.4. Input and Output Variables

The study considered D, O, and S as the input factors. The outcome of the variable is FRPN.

4.5. Input and Output Variables

Experts submitted the failure mode O, S, and D scores generated in earlier steps. The scores obtained from the professionals are listed in Table 6.

According to the literature, the arithmetic mean (AM) and geometric mean (GM) were both used for ratings assigned by multiple experts. The AM is a simple average calculated by summing all the scores and dividing by the number of scores. This method is straightforward to understand. It works well when the dataset is relatively uniform and the scores are not significantly skewed. The geometric mean, on the other hand, is calculated by multiplying all the scores together and then taking the nth root, where n is the number of scores. This method is particularly useful when dealing with multiplicative data or when the data span several orders of magnitude. When conducting FMEA evaluations, the AM and GM approaches can be utilized interchangeably, as comparative studies have demonstrated that they yield highly similar results [55]. An examination of other FMEA studies in the existing literature indicates that both methods were employed. However, considering the FMEA's multiplicative nature, the GM might be more suitable for aggregating multiple experts scores because it mitigates the impact of outliers and provides a more robust measure of central tendency. This is especially important in risk assessment, where the goal is to obtain a reliable estimate of potential failure risks while preventing extreme values from disproportionately influencing the results. In this regard, the GM method was selected, which is a frequently preferred approach that estimates the GM of the multiple O, S, and D scores for this investigation [56]. The expert scores transformed a form suitable for fuzzy analysis by computing the GM. The expert scores geometric means are computed using the GM formula, as depicted in Equation (2).

$$\bar{X}_{geom} = \sqrt[n]{x_1 \times x_2 \times x_3 \times \ldots \times x_n} \qquad (2)$$

As an additional feature, the GM, O, S, and D values for each failure scenario are presented in Table 6.

4.6. FFMEA Model

The research is preoccupied with supplying inputs to the model and extracting outputs from the inference engine. Three input components constitute the methodological framework: O, S, and D. Input MF represent the input. The fuzzy inference engine is then provided with the inputs by using the MFs. The inference mechanism evaluates the current inputs based on the rule base. The MF for the generated outputs is then established. To assess the risks, prioritizing the RPN of identified cases is necessary. Nevertheless, in fuzzy expert systems, the final outcome following the inference stage is a fuzzy value. Accuracy and clarity of the imprecise data acquired from the fuzzy inference system are necessary. The output MF are used to achieve this objective. After fuzzification and fuzzification, the outputs (FRPN scores) are obtained. Figure 3 illustrates the FFMEA model.

4.7. Input and Output MF

Various MF can be used, such as the Gaussian MF (GMF), the trapezoidal MF (ZMF), and the triangular MF. In theory, the ZMF comprises four components denoted as s, t, u, and v. Equation (3) defines the function that determines the membership of a trapezoidal fuzzy set x= (s, t, u, v; w). The MF of variable x is denoted A (x). A normalized trapezoidal function is defined as x= (s, t, u, v; 1) when w=1.

Table 5. *Expert profiles of the study*

Expert number	International STCW competency	On-board experience	Current position
Expert No. 1	Ocean-going Chief Engineer	˃ 15-year experience	Ship Management Company: Marine Engineering Technical Inspector
Expert No. 2	Ocean-going Chief Engineer	˃ 15-year experience	Ship Management Company: Chief Engineer
Expert No. 3	Ocean-going Chief Engineer	˃ 15-year experience	Ship Management Company: Chief Engineer
Expert No. 4	Ocean-going Chief Engineer	˃ 15-year experience	Ship Management Company: Chief Engineer
Expert No. 5	Ocean-going Chief Engineer	˃ 15-year experience	Ship Management Company: Chief Engineer

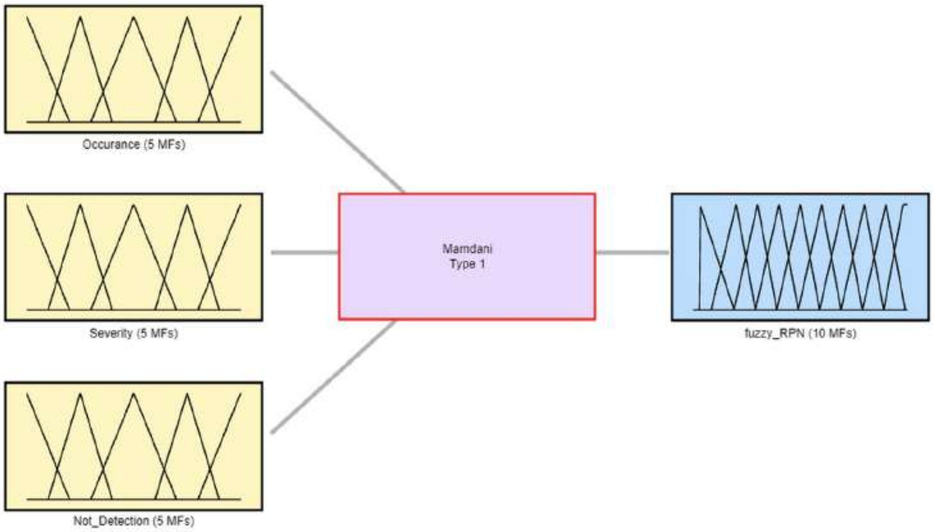


Figure 3. *FFMEA model of the study*

FFMEA: Fuzzy failure mode effect analysis

Table 6. *Expert scores of the ship bunkering operations*

FM	O_1	O_2	O_3	O_4	O_5	S_1	S_2	S_3	S_4	S_5	D_1	D_2	D_3	D_4	D_5	GM O	GM S	GM D
FM01	8	10	6	9	7	3	4	4	3	6	7	5	8	8	7	7.87	3.87	6.90
FM02	1	3	2	1	1	8	5	6	6	8	2	4	5	6	5	1.43	6.49	4.13
FM03	4	5	6	5	4	6	7	6	6	8	5	6	8	7	6	4.74	6.55	6.32
FM04	4	2	5	3	3	5	8	8	7	8	4	5	9	5	5	3.25	7.09	5.38
FM05	6	9	8	5	7	6	8	7	6	9	5	4	8	6	5	6.85	7.11	5.45
FM06	1	3	1	2	1	5	4	4	4	5	9	10	8	9	8	1.43	4.37	8.77
FM07	3	2	2	3	3	3	4	4	5	5	2	1	5	3	4	2.55	4.13	2.61
FM08	2	1	2	2	2	6	6	6	5	5	5	8	9	8	9	1.74	5.58	7.63
FM09	5	3	2	3	2	7	6	6	6	6	5	7	8	5	8	2.83	6.19	6.45
FM10	7	6	7	5	6	4	7	7	5	5	6	4	3	6	7	6.15	5.47	4.97
FM11	2	1	1	3	2	8	10	10	9	9	5	6	3	6	5	1.64	9.17	4.86
FM12	3	3	5	3	4	7	8	9	8	9	2	4	3	5	4	3.52	8.16	3.44
FM13	6	4	7	5	5	7	10	9	8	8	3	3	2	2	2	5.30	8.34	2.35
FM14	4	7	5	7	4	5	6	7	5	7	5	7	4	6	5	5.23	5.93	5.30
FM15	3	2	3	2	3	7	5	5	5	5	2	3	4	4	5	2.55	5.35	3.44
FM16	1	1	2	2	2	6	7	5	7	7	1	2	2	2	3	1.52	6.35	1.89
FM17	6	4	4	4	3	8	6	6	4	8	4	6	5	3	6	4.10	6.21	4.64
FM18	6	4	4	4	6	9	8	6	8	8	7	8	9	8	7	4.70	7.73	7.76
FM19	8	9	6	9	7	9	9	7	7	9	5	4	5	5	4	7.71	8.14	4.57
FM20	1	1	2	1	1	9	8	8	8	7	1	1	2	2	2	1.15	7.97	1.52
FM21	2	3	1	1	1	8	10	10	9	9	2	3	6	3	5	1.43	9.17	3.52
FM22	1	1	2	1	1	8	10	10	9	8	1	2	1	2	2	1.15	8.96	1.52
FM23	2	5	3	2	2	5	5	4	6	3	5	10	6	7	6	2.61	4.48	6.61
FM24	1	4	1	1	2	3	5	5	4	3	2	2	1	2	2	1.52	3.90	1.74
FM25	5	3	4	3	2	3	6	5	4	4	5	6	4	5	9	3.25	4.28	5.58
FM26	3	3	2	2	2	2	3	3	2	5	3	4	7	5	6	2.35	2.83	4.79
FM27	4	5	4	5	3	5	3	4	3	5	5	8	5	5	5	4.13	3.90	5.49

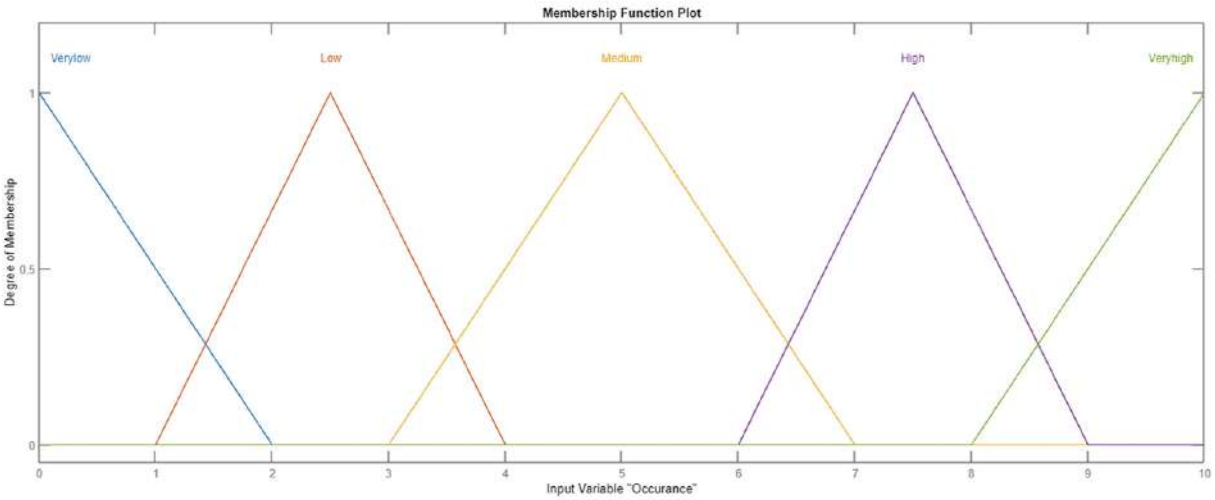


Figure 4. *Input triangular membership functions*

$$\mu A(x) = \begin{cases} \dfrac{w(x-s)}{t-s}, & s \leq x \leq t \\ w & t \leq x \leq u \\ \dfrac{w(s-v)}{u-v}, & u \leq x \leq v \\ 0, & otherwise \end{cases} \tag{3}$$

If the value of t is equal to u, then it is possible to simplify the trapezoidal fuzzy set to a triangular fuzzy set using Equation (4).

$$\mu A(x) = \begin{cases} 0, & x \leq s \\ \dfrac{x-s}{t-u}, & s < x \leq t \\ \dfrac{v-x}{v-t}, & t < x < v \\ 0, & x \geq v \end{cases} \tag{4}$$

The GMF, which is a fundamental component for modeling uncertainty in fuzzy logic systems, is expressed in Equation (5).

$$\mu A(x) = e^{\frac{-(x-m)^2}{2\sigma^2}} \tag{5}$$

The variables denoted as "m" and "σ" correspond to the AM and standard deviation, respectively [57]. The triangle MF is frequently used in academic research, especially for risk assessment, among several types of MF [58]. In addition, a triangle fuzzy MF with 5 levels was employed in this study due to its user-friendly nature. As shown in Figure 4, there are five distinct zones within the function, including the "very low", "low", "medium", "high", "very high" sections.

In contrast, the study's output MF employed a triangle MF with ten levels. As shown in Figure 5, the functional framework comprises 10 distinct zones: "none", "very low", "low", "high-low", "low-medium", "medium", "high-medium", "low-high", "high", "very high".

4.8. Rule Base

The model employs if-then rules to generate FRPN outputs as part of its inference mechanism. A 5-level input MF of O, S, and D was employed in this study. Hence, the study's rule base has 125 (5x5x5) if-then rules. Equation (6) presents the initial form of fuzzy rules.

Ri: IF o is Oi, s is Si, and d is Di, then RPN is

Ri = 1, 2, …, K (6)

Here, Ri represents the rule number, K represents the total number of rules, variables o, s, and d are antecedents, input fuzzy sets are Oi, Si, Di, and Ri, and RPN refers to the end variable. The following are a few examples of fuzzy If-then rules:

IF "O" is low and "S" is low and "D" is high, then "FRPN" is a low medium.

IF "O" is medium and "S" is medium and "D" is High, then "FRPN" is high.

IF "O" is very high and "S" is very high and "D" is high, then "FRPN" is very high.

4.9. Inference Engine

The existing literature proposes several different approaches to fuzzy inference systems, including Takagi Sugeno Kang, Mamdani, and Tsukamoto. These approaches vary according to the intended output. According to the literature, a more natural and human-like definition of expertise has been made possible by the Mamdani method [59]. Because

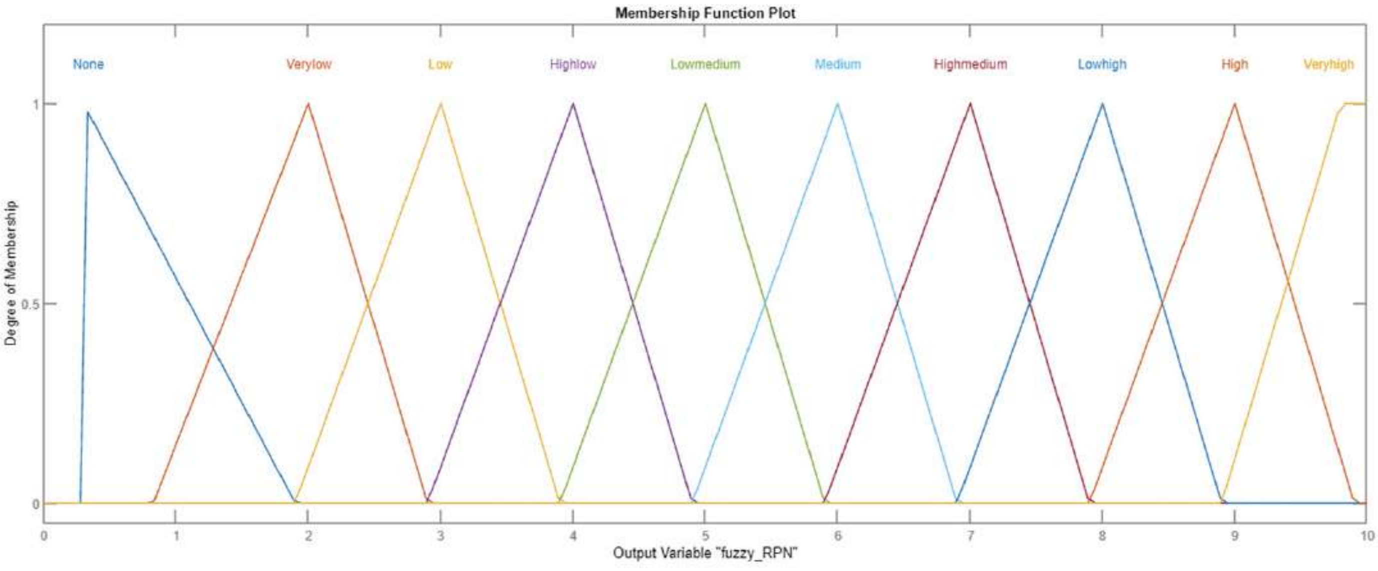


Figure 5. *The output triangular membership function*

of this, the Mamdani technique is used most often in the interface of academic studies software to combine non-linear components [60,61]. The inference approach minimizes the input and maximizes the aggregate. This approach was implemented to mitigate the issues associated with the use of multiplicative sums. The equation provided in Equation (7) is used for this method.

$$\mu_{Ri''}\ (\mathrm{RPN})=\max_{i=1,2,\ldots K}(\mu_{Ri''}\ (RPN)) \tag{7}$$

Several defuzzification methods have been described in the literature, such as the mean of the largest values method, the center of gravity (COG) method, the two regions method, the center of total values method, and the arranged height method. As stated in the literature, the center-of-gravity method is widely recognized as the primary fuzzification methodology, particularly in the context of FFMEA risk analysis [51,62]. In this study, the COG was used for defuzzification. Equation (8) represents the mathematical expression for the center of gravity.

$$COG=\frac{\int_a^b \mu\mathrm{A}\ (\mathrm{X})\ \mathrm{xdx}}{\int_a^b \mu\mathrm{A}\ (\mathrm{X})\ \mathrm{xdx}} \tag{8}$$

4.10. FRPN Outputs

A calculation is made using Equation (1) to determine the RPN of the per-failure. Through the process of inputting the GM, O, S, and D into the study's model, FRPN values were obtained. To illustrate the application of the fuzzy rules, an example is provided for FM18-incorrect valve operations. Based on the GM values derived from the expert assessments, the inputs for this failure mode were O (O=4.70), S (S=7.73), and D (D=7.76). These values were first quizzified into linguistic labels using triangular MFs. The fuzzification process mapped O to "medium" (membership degree: 0.7) and "high" (membership degree: 0.3), S to "high" (membership degree: 0.8) and "very high" (membership degree: 0.2), and D to "high" (membership degree: 0.9) and "very high" (membership degree: 0.1). Subsequently, the fuzzy inference system applies relevant rules from the 125-rule fuzzy rule base. For example, the rule "If O is medium and S is high and D is high then FRPN is high-medium" contributed significantly with a weighted output of 0.7×0.8×0.9=0.504. Another rule, "If O is high and S is high and D is very high then FRPN is high" contributed 0.3×0.8×0.1=0.024. The fuzzification process, which uses the COG method, aggregates the contributions from all relevant rules. Adjustments were made to align the weights and crisp values with the fuzzy logic model. For instance, crisp values of 6.8 for "high-medium" and 7.5 for "high" were used. The contributions were calculated as 6.8×0.57=3.876 and 7.5×0.04=0.3. The final defuzzified FRPN was calculated as (3.876+0.3)/(0.57+0.04)≈6.93. The high contribution of rules involving "high" and "very high" S and D values reflects the critical nature of FM18. This result emphasizes the importance of the rule base in accurately capturing and weighing expert assessments. The rules assigned a higher weight to situations where D and S were significant, underscoring the necessity of strict valve operation protocols and enhanced D systems to effectively mitigate the risks associated with this failure mode. This robust rule-based framework ensures that the most critical failure modes are prioritized accurately for risk mitigation. The corresponding outputs of the study (FRPN) are shown in Figure 6.

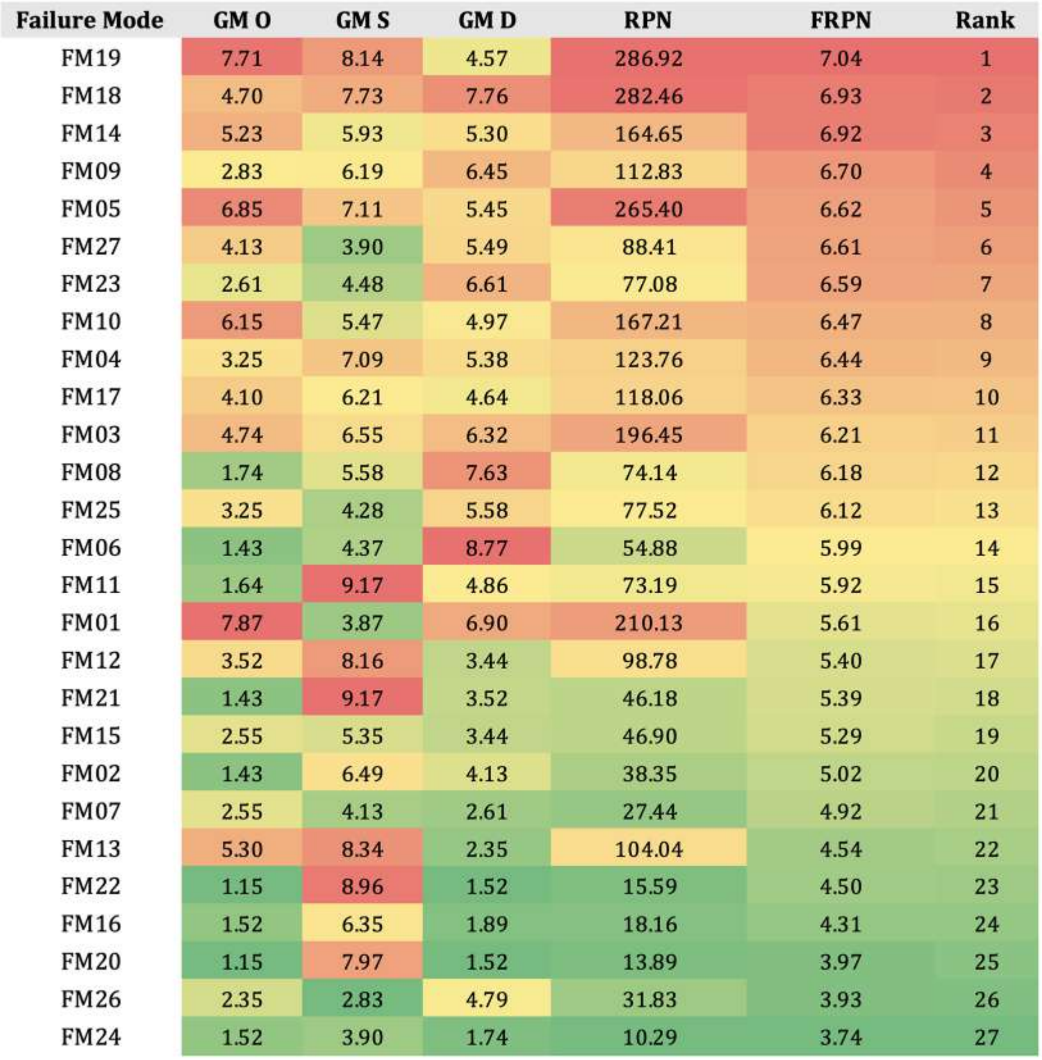
5. Discussion

The rule-based FFMEA method was used to identify the failure modes and assign corresponding weights. The analysis results yielded the following rankings based on FRPN values: FM19 (7.04), FM18 (6.93), FM14 (6.92), FM09 (6.70), FM05 (6.62), FM27 (6.61), FM23 (6.59), FM10 (6.47), FM04 (6.44), FM17 (6.33), FM03 (6.21), FM08 (6.18), FM25 (6.12), FM06 (5.99), FM11 (5.92), FM01 (5.61), FM12 (5.40), FM21 (5.39), FM15 (5.29), FM02 (5.02), FM07 (4.92), FM13 (4.54), FM22 (4.50), FM16 (4.31), FM20 (3.97), FM26 (3.93), FM24 (3.74).

FM19, which is the most critical failure mode with an FRPN score of 7.04, is defined as the "lack of proper control mechanisms." This failure mode had notably high average values for O frequency (GM O) and S (GM S). Continuous monitoring of several factors, including the pressure, tank level, and circuit leakage, is essential at each stage of the bunkering operation. These controls enable the D and correction of faults in other components prior to an accident. Control mechanisms are widely acknowledged as vital elements of modern automation systems, acting as highly effective preventive measures in both manual and automatic operations.

FM18, "incorrect valve operations" ranked second with an FRPN of 6.93. This failure mode is particularly significant because of its high GM S and GM D values. Failing to close valves at the start of the bunkering operation or opening them incorrectly can lead to leaks in the bunker/fuel line, fuel leakage, hose rupture, or fuel transfer to an incorrect tank. Furthermore, the capacity to detect improperly executed valve actions is exceedingly limited. Enhancing human factors is crucial for effectively mitigating the risks linked to this failure mechanism because it directly influences decision-making, situational awareness and adherence to company procedures.

In third place, FM14, "Ineffective communication between ship crew and shore or barge personnel" is ranked with an



Failure Mode	GM O	GM S	GM D	RPN	FRPN	Rank
FM19	7.71	8.14	4.57	286.92	7.04	1
FM18	4.70	7.73	7.76	282.46	6.93	2
FM14	5.23	5.93	5.30	164.65	6.92	3
FM09	2.83	6.19	6.45	112.83	6.70	4
FM05	6.85	7.11	5.45	265.40	6.62	5
FM27	4.13	3.90	5.49	88.41	6.61	6
FM23	2.61	4.48	6.61	77.08	6.59	7
FM10	6.15	5.47	4.97	167.21	6.47	8
FM04	3.25	7.09	5.38	123.76	6.44	9
FM17	4.10	6.21	4.64	118.06	6.33	10
FM03	4.74	6.55	6.32	196.45	6.21	11
FM08	1.74	5.58	7.63	74.14	6.18	12
FM25	3.25	4.28	5.58	77.52	6.12	13
FM06	1.43	4.37	8.77	54.88	5.99	14
FM11	1.64	9.17	4.86	73.19	5.92	15
FM01	7.87	3.87	6.90	210.13	5.61	16
FM12	3.52	8.16	3.44	98.78	5.40	17
FM21	1.43	9.17	3.52	46.18	5.39	18
FM15	2.55	5.35	3.44	46.90	5.29	19
FM02	1.43	6.49	4.13	38.35	5.02	20
FM07	2.55	4.13	2.61	27.44	4.92	21
FM13	5.30	8.34	2.35	104.04	4.54	22
FM22	1.15	8.96	1.52	15.59	4.50	23
FM16	1.52	6.35	1.89	18.16	4.31	24
FM20	1.15	7.97	1.52	13.89	3.97	25
FM26	2.35	2.83	4.79	31.83	3.93	26
FM24	1.52	3.90	1.74	10.29	3.74	27

***Figure 6.** Traditional and Fuzzy RPN outputs of the study*

RPN: Risk priority number

FRPN of 6.92. In this failure scenario, the inputs for GM O, GM S, and GM D are all above-average. Inadequate communication within the ship or between the ship and the barge or shore facility during bunkering can lead to numerous errors. To mitigate this risk, it is advisable to enhance communication proficiency, provide modern technology that facilitates uninterrupted communication, or employ efficient foreign language capabilities.

Equally significant, FM09 (6.70), identified as "non-operational bunker level monitoring systems", was ranked as the fourth most critical failure mode. The primary factor contributing to its risk is difficulty in D. Before, during, and after fuel bunkering, monitoring systems measure tank levels, thereby aiding in managing the entire process. Malfunctioning monitoring systems can cause users to mislead, resulting in incorrect fuel calculations within the tank and undesirable situations, such as fuel overflow.

FM05, with an FRPN of 6.62, represents "inadequate planning and lack of pre-bunkering meetings" and is the fifth most critical failure mode. This mode has average GM values for O (GM O) and S (GM S). Bunkering is a multifaceted operation that requires coordinated and preplanned teamwork among various ship personnel, including the chief engineer, third engineer, donkeyman, fitter, and oiler. Effective planning before operation, clearly assigning each crew member's duties, and scheduling necessary checks are crucial.

The lowest priority with an FRPN value of 3.74 is FM24, "absence of material safety data sheets for bunker fuel." This indicates a relatively lower risk than other identified failure modes.

When examining the results of other studies that have conducted risk analyses on bunkering operations, Kamal and Kutay [5] approached the issue from an environmental perspective. They identified major pollution-related factors as overflow, operational causes, and crew-related causes. Similarly, Akyuz et al. [4] investigated bunkering risks with a focus on human factors. Their findings indicate that both pre-and during-bunkering operations exhibit relatively high human error probabilities (HEPs). Specific subtasks contributing to these high HEPs include low pumping at the beginning of the operation, continuous monitoring of the bunkering process, and issues such as plugged deck scuppers. On the other hand, Çiçek and Topcu. [39] highlighted failures such as inadequate control of checklists, system calibration issues, gauge errors, non-compliance with the fuel bunkering plan, and communication deficiencies as unacceptable risk levels. Furthermore, Doganay et al. [40] identified periodic inspections of level sensors in fuel tanks and pre-operation sounding measurements as critical factors. These steps ensure accurate monitoring and prevent operational risks. Many of the high-risk findings identified in previous studies were similarly ranked among the highest FRPN values in this research, underscoring the consistency and corroborative nature of this study with prior investigations. Additionally, while the majority of literature predominantly focuses on human error, this study broadens the analytical framework by incorporating the technical failures associated with contemporary technological components, such as machinery and software. By addressing these technical dimensions, this study offers a comprehensive analysis of risk factors in bunkering operations, thus contributing to a deeper understanding of the multifaceted nature of operational risks.

6. Conclusion

Ships require a continuous supply of fuel to maintain their commercial functions, which necessitates frequent execution of ship bunkering operations. Despite the critical nature of these operations for the sustenance of maritime activities, they inherently encompass a multitude of risks. The ramifications of such risks are considerable, posing severe threats to cargo integrity, human safety, and environmental preservation. Consequently, a thorough examination and identification of these hazards are imperative to prevent accidents associated with bunkering activities. This study, therefore, undertakes a comprehensive risk analysis of ship bunkering operations, motivated by the objective of enhancing safety protocols and mitigating potential hazards.

The findings quantitatively reveal the risks associated with bunkering operations. The analysis identified the most hazardous failure modes as lack of proper control mechanisms (7.04), incorrect valve operations (6.93), and ineffective communication between the ship crew and the shore or barge personnel (6.92).

The findings of this study hold significant implications for regulatory compliance, particularly concerning international maritime safety and environmental standards, such as those outlined by the IMO and The International Convention for the Prevention of Pollution from Ships. The prioritization of critical failure modes, such as improper valve operations and ineffective communication, can directly inform the design of regulatory protocols and ship-specific safety procedures. By integrating advanced risk assessment methodologies like FFMEA, shipping companies and regulatory bodies can proactively address operational risks, ensure adherence to environmental standards, and minimize the likelihood of non-compliances. Furthermore, these results offer practical insights for the development of training modules and operational checklists to enhance crew preparedness and system reliability. Ship bunkering operations exert significant environmental repercussions globally. Therefore, implementing a comprehensive risk assessment in this area is essential for mitigating the incidence of such accidents. The findings of this study have provided maritime stakeholders with a detailed quantitative risk ranking specific to bunkering operations. An accurate understanding of these risks, coupled with the implementation of proactive measures, will effectively mitigate or minimize the consequences of potential accidents.

The primary limitation of this research is the unavailability of professionals with over 15 years of ship experience, particularly those who have supervised numerous bunkering operations as chief engineers. Consequently, the study relied on input from five marine experts for analysis. While their expertise significantly contributed to the reliability of the findings, the inclusion of a more diverse panel of experts could enhance the robustness of future analyses. Expanding expert selection to include regulatory officials, port authorities and academic researchers would provide a broader spectrum of operational insights and regional variations, improving the generalizability and applicability of the risk assessment framework. Future studies should also explore hybrid risk analysis methods tailored to alternative fuels, such as methanol and ammonia, to address both emerging risks and evolving regulatory requirements in maritime operations.

Ethics

Ethics Committee Approval: The study was approved by the Bandırma University Onyedi Eylül University Science and Engineering Ethics Committee (approval no.: 2024/01, date: 11.11.2024).

Footnotes

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Türkiye's Maritime Training and Education Institutes Non-Conformities Historical Evaluation by Grey Relation Analysis and Geographical Information System

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Abstract

The main aim of the study is to determine an objective method for maritime training and education institutes quality assessment based on objective data. To achieve this, results of external audits carried out by independent evaluation are analysed using the Entropy Weighted Grey Relation Analysis method. In the final stage, results of Entropy Weighted Grey Relation Analysis method are demonstrated on QGIS, an open source Geographic Information System, thus Türkiye maritime training and education institutes non-conformities concentration and distribution maps are generated.

Keywords: Maritime training and education, Quality assessment, Grey relation analysis, Geographic information system, Non-conformities

1. Introduction

Maritime training and education governed by national and international regulations and all maritime training and education institutes needs to comply with these regulations in order to certify their students /trainees. The Standards of Training, Certification and Watchkeeping of Seafarers International Convention (STCW-1978) and amendments prescribe minimum standards relating to training, certification and watchkeeping for seafarers, which all countries need to comply with. National maritime administrations ratify and implement the STCW-1978 Convention, the STCW Code, and their amendments. Turkish Maritime Administration ratified STCW Convention and regulate its national maritime training and education institutes with legislations including "Regulation for Seafarers and Sea Pilots" and "Directive for Seafarers and Sea Pilots Training and Examination" which are prepared in reference to STCW-1978 Convention and STCW Code as amended.

Compliance with national and international regulations is checked by audits in accordance with the "Directive for Seafarers and Sea Pilots Training and Examination". An initial audit, as a pre-condition of accreditation, and 2-year periodic audits are carried out. However, there are no studies found on these audits' results which can help to identify the weakness of the maritime training and education institutes or how training quality can be improved in these institutes.

There are 168 maritime training and education institutes, of which 20 offer associate degrees, 26 offer bachelor degrees, 52 offer high school degrees, and 70 offer private courses in Türkiye as of December 2020 [1]. Audit results of Turkish Maritime training and education institutes are kept in a software called GAEBS, under the control of the Ministry of Transport and Infrastructure, which is also recognized as Türkiye's Maritime Administration. Table 1 shows the distribution of maritime training and education as per their education degrees, their accreditation from Administration, and their geographical distribution.

Data acquired from GAEBS is analysed by entropy-weighted Grey Relation Analysis (GRA), and the grey relation coefficient of each non-conformity category is determined. This analysis is then applied to non-conformities categorized by geographical distribution.

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Table 1. *Geographical distribution of Türkiye's maritime training and education institutes*

Province	**Assoc. Degree**		**Bachelor Degree**		**Highschool**		**Private Training Centers**		**Total**
	Accredited	**None-Accredited**	**Accredited**	**None-Accredited**	**Accredited**	**None-Accredited**	**Accredited**	**None-Accredited**	
Bartın	1								1
Kastamonu					1				1
Aydın				1	2				3
Bitlis					1			1	2
Tekirdağ					1				1
Van				1	1				2
Zonguldak	1			1	1				3
Yalova	1				1				2
Çanakkale				1	1		1		3
Hatay			1		1			1	3
Sinop		1				2		1	4
KKTC	1		2						3
Balıkesir				1	2			2	5
Ordu	1		1		1			2	5
Giresun		1		1	3			1	6
Kocaeli	1		1		2		2		6
Rize			1		3		1		5
Samsun				1	1		3	2	7
Antalya				1	2		2	3	8
Trabzon		1	1		1	2	1		6
Mersin	1			1	2		3		7
Muğla	1				5		6	5	17
İzmir	1		1	1	5	2	2	9	21
İstanbul	4	3	5		6	2	11	10	41
Adana				1		1			2
Bursa				1				1	2
Sakarya		1							1
Gaziantep				1					1
Total	13	7	13	13	43	9	32	38	168

The result of Entropy Weighted GRA is demonstrated on QGIS, an open source Geographic Information System (GIS), and thus, maps of non-conformities analysis of Türkiye are generated.

2. Literature Review

In the literature, much research have been found on GRA, in which for different areas. However, no specific study on maritime training and education institutes, quality assessment of training institutes, or segmentation using of GRA is found. Lin et al. [2] used the GRA method to assess watermarking schemes in digital multimedia copyright protection. Vatansever and Akgul [3] applied entropy and GRA method to determine airlines websites performance evaluation.

Another example of use of entropy and GRA is found by Lee et al. [4] in which financial positions of two shipping companies are compared by this method.

Kokoç and Ersöz [5] found 119 publications regarding the perception of service quality offered by higher education institutions. Some of the scales used in the evaluation of service quality of higher education institutions are ClassroomQual, EduQUAL, HedQUAL, HedPERF (stands for Higher Education Performance) HESQUAL, INSTAQUAL, SERPERF (stands for Service Performace), Student Satisfaction Scale, SERVQUAL (stands for Service Quality) and UNIQUAL. In fact, there are scales developed by researchers using different service quality measurements and criteria. The most commonly used criteria that can be counted are physical facilities, reliability and security, sensitivity/empathy, fees, academic staff, transport facilities, and infrastructure. In scales developed in recent years, new criteria such as academic attendance, cognitive attendance, training quality, academic staff profiles, curriculum, infrastructure, and facilities have become the main measurements in these scales. However, common specifications of these scales are mostly subjective and based on questionnaires. In fact, some of the studies mentioned that these scales are insufficient to determine the service quality of higher education institutes [5].

Saeidi et al. [6] have used the SERVQUAL standard questionnaire to evaluate the service of maritime training institutions while Dacuray et al. [7] used a descriptive type of research in their study on Maritime Students' Satisfaction with the Services of one Training Center in the Philippines.

Only one study by Chen et al. [8], using entropy weighted GRA, is used in the maritime field in which port state control results are analysed by this method.

In the literature review of maritime training and education institutes, research is usually carried out by comparison of quantitative data, such as the number of trainers, the number of students, or the facilities of the institutes. No study has been found, based on non-conformities in the training institutes. Similarly, no research is found in the area of maritime training and education institutes segmentation by the GISs.

The application of the entropy-weighted GRA method to analyse non-conformities of maritime training and education institutes, and the demonstration of results using GIS, makes this research an objective assessment method never used before.

3. Application

3.1. Entropy Weighted GRA

Grey Relation theory was formulated by Ju-Iong Deng in 1982, and it is a mathematical method that can be applied interdisciplinarily. It is especially useful when the datasets are not sufficient to run statistical analysis [9].

GRA is a decision-making method, to be used to generate discrete sequences for the correlation analysis of such sequences with processing uncertainty, multi-variable input, and discrete data [2]. Also, the ability to work with small and uncertain data sets makes this method preferable to other statistical methods [10,11].

GRA is independent of a probability distribution. It gives more reliable results with small data sets, especially when compared to statistical analysis [12].

However, where inconsistent dimensions or data types makes use of conventional GRA insufficient, method is improved by entropy weight method. Integrated method of entropy weighted GRA is used frequently in technical areas and engineering [8]. The entropy weighted method reflects the real importance of each factor in the system.

3.2. Methodology

In this study, Entropy Weighted GRA is applied to audit results of the Directive for Seafarers Training and Examination for audits carried out between 2011 and 2017 at Turkish Maritime Training and Education Institutes. Data obtained from the software called GAEBS (Seafarers Training Information System) with written permission of Ministry of Transport and Infrastructure. With this analysis, grey relational coefficient and ranking for each non-conformity category are determined.

In the second step of the analysis, by using grey relation coefficient, maritime training institute non-conformities calculated by their geographical distribution.

In the final step of the study, the geographical distribution of GRA results is demonstrated by using QGIS.

3.3. Datasets

Information and audit results of Turkish Maritime Training and Education Institutes are stored and managed by software called GAEBS, which stands for Seafarers Training Information System. In this database, information such as, capacity, departments, infrastructure and facilities, lecturers, audit reports, and other details of the institutes are kept. With official permission from the Administration, data on the 117 training institutes and their audit results, which were carried out in accordance with the Directive on Seafarers Training and Examination for the period between 2011 and 2017, were obtained.

In this respect, 2,086 non-conformities are used as raw data. This data is classified as Documentation, Lecturer, Equipment, Curriculum, Simulator Specifications and System Non-conformities categories. The raw data are filtered against uncertainties and 861 non-conformities are used in the analysis.

3.4. Entropy Weighted GRA Analysis of Turkish Maritime Institutes Audits Results

The aim of this study is to establish a quality assessment model for maritime training and education institutes and find the degree to which the non-conformities found in the audits affect the outcomes. In order to do this, GRA and Entropy Weight Method are integrated. In the first step, non-conformities are categorized, and the GRA method with the entropy weight model is applied. Methodological framework of the process is given in Figure 1 and steps of GRA of the data is given in Table 2.

3.5. Application of Entropy Weighted GRA on Non-conformities Based on Cities Distribution

Steps of GRA given in Figure 1 are applied to non-conformities found in the audits. These non-conformities are categorized and distributed according to the geographical location of the respective maritime training institute. A decision matrix is formed by these categorisations (Table 3).

Further calculations are carried out by using formulas given in Table 2. In the next step, a "normalised decision matrix" is formed. At this step, there are 3 approaches, namely the Benefit Approach, the Reduction Approach, and the Mean Approach. In our study, a reduction approach, which means "smaller is better," is used since the aim is to reduce the non-conformities.

In the third step the analysis entropy weights are calculated and "entropy measure matrix" is formulated. The calculation results are the distance between the normalized value and the reference criteria series in terms of absolute value.

The next step is the calculation of the absolute value of the criteria matrix. Calculated results are reflected in the study findings. Reference series and minimum and maximum values are determined.

In the last step of the GRA, objective weight for each criteria is calculated and Grey Relation Coefficient (ε_j) matrix formed (Table 4). Grey Relation Coefficient (ε_j) is the objective weight of each criterion, thus showing the importance of the effect of non-conformities on the training institute quality assessment.

The Grey analysis process is repeated for the non-conformities recorded between 2011 and 2017, and the Grey Relation Coefficient (ε_j) is found for each category. Accordingly, the following results were returned from the calculation (Table 5).

According to the GRA of the non-conformities found in the audits, the ranking of the grey relation coefficients is as follows: Equipment (1.137), Curriculum (1.055), Documentation (0.762), Simulator Specifications (0.602), System Non-conformities (0.338) and Lecturer (0.145). The above-mentioned relation coefficients (ε_j) are applied to entropy weights to obtain grey relation degrees of each category by cities distribution, and results are shown in Table 6.

4. Demonstration of The GRA Results on GIS

GRA has been applied to the audit results of 117 training institutions carried out between 2011-2017, and results of the analysis are applied to non-conformities of 14 cities selected based on a useful dataset.

Results of GRA analysis are demonstrated using QGIS, an open-source GIS. With the help of GIS, segmentation map of entropy weighted grey relation coefficients of non-conformities factors have been generated.

According to this GRA analysis, "Equipment" category has returned the highest GRA coefficient of 1.137. The distribution map of GRA coefficients for each non-conformities category is formed by using QGIS.

In the equipment category, which has the highest GRA coefficient, the densest cities are observed to be Kocaeli and Ordu. These provinces are followed by Mersin, Balıkesir, and Çanakkale respectively. The provinces with the least density in the equipment category were Giresun and Antalya.

The primary aim of the study is to see the distribution of non-conformity categories throughout Türkiye and create charts of these distributions. On the other hand, these findings will only be useful through root cause analysis and addressing root causes. Therefore, sampling is conducted on Non-conformities Correction Forms, and root causes are assessed.

Among the root causes of non-conformities in the equipment category is the insufficient financial resources required for

Table 2. *Entropy weighting and grey relation analysis process*

	Entropy weighting	Grey relation analysis
Step 1	Construction of a decision matrix (X). A set of alternatives (A= {A_i. i=1.2,…,n}), compared with a set of criteria (C= {C_i ,i=1,2,…,n}). Therefore, an n×m performance matrix (the decision matrix; X) can be obtained as follow: $X= \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix}$ where X_{ij} is a crisp value indicating the performance rating of each alternative A_i with regard to each criterion C_j.	A decision matrix is constructed with original data. $X = \begin{bmatrix} x_1(1), x_1(2), \ldots\ldots x_1(n) \\ x_2(1), x_2(2), \ldots\ldots x_2(n) \\ \ldots\ldots \\ x_m(1), x_m(2), \ldots\ldots x_m(n) \end{bmatrix}$
Step 2	To ascertain objective weights by the entropy measure, the decision matrix in Step 1 needs to be normalized for each criterion C_j (j=1,2,...., m) as $p_{ij}=\frac{x_{ij}}{\sum_{p=1}^{n} x_{pj}}$, $i=1,2,....n$ $P = \begin{bmatrix} p_{11} & \cdots & p_{1m} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nm} \end{bmatrix}$	Standard data normalization formulas: I) Benefit approach (Larger is better): $x_i(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)}$ or II)Reduction approach (Smaller is better): $x_i(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)}$ or III)Mean approach (Nominal is best): $x_i(k) = \frac{\lvert x_i(k) - x_0(k) \rvert}{\max x_i(k) - x_0(k)}$
Step 3	Calculate the entropy measure of every index using the following equation: $e_j = -k\sum_{i=1}^{n} p_{ij} \ln p_{ij}$, Where k=1/ln(n)	For determination grey relation ranking I) Calculate the distance between normalized value with reference criteria series by absolute value: $\Delta x_i(k) = \lvert x_0(k) - x_i(k) \rvert$ II) Find reference sequence. III) Determine min. and max. values IV) Use (distinguishing coefficient) p=0.5.
Step 4	The degree of divergence (d_j) of the average intrinsic information contained by each criterion (C={C_j ,j=1,2,…,m}) can be calculated as: $d_j = 1 - e_j$ the more d_j is, the more important the criterion jth. is.	Calculate the grey relational degree (ξ) and degree of grey coefficient (r_i) $\xi_i(k) = \frac{\Delta \min + p\Delta max}{\Delta x_i(k) + p\Delta max}$ $r_i = \sum[w(k)\xi(k)]$
Step 5	The objective weight for each criterion (C= {C_j, j=1,2,…,m}) is thus given by: $w_j=\frac{d_j}{\sum_j d_j}$	

Vatansever and Akgul [3]

purchasing or renewing equipment. The difficulty of the budget approval process for equipment requests in public training institutions makes it challenging to eliminate these inconveniences. Private training institutions try to minimize their expenses, as they eventually carry out a commercial activity with profit maximization aims.

Maritime training institutions should have maritime safety training centers in order to carry out STCW courses. These training centers consist of fire training centers, life-saving appliances (lifeboats, etc.), and survival at sea training facilities (pools or water areas with jumping platforms). In addition to the size of the initial investment cost of these facilities, the difficulty in obtaining sea and water area permits also contributes negatively to this category. For this reason, many training institutions have chosen to operate a shared training center or sign a protocol to use the facility of another institution during training periods.

The second highest GRA coefficient category is the Curriculum. The density map for this category shows that the highest density is in Samsun and Mersin provinces. These provinces are followed by İstanbul and Trabzon.

The root cause of the non-conformity in this category is considered to be the delays in the inclusion in the curriculum

Table 3. *Non-conformities frequency matrix by city distribution*

	Documentation	Lecturer	Equipment	Curriculum	Simulator specs.	System non-conformities
Antalya	12	15	59	3-	2	5
Balıkesir	14	18	9	0	0	10
Çanakkale	11	14	17	0	0	8
Giresun	0	15	31	2	3	0
Mersin	36	31	110	23	5	15
İstanbul	112	89	178	52	38	77
İzmir	46	34	47	12	8	36
Kocaeli	27	18	99	7	9	5
Muğla	33	34	96	17	23	24
Ordu	26	9	23	6	7	4
Rize	7	11	32	1	2	0
Samsun	9	12	10	6	0	8
Sinop	2	1	22	0	0	0
Trabzon	5	6	5	4	0	4

Table 4. *Grey relational coefficients (ε_i) distributions by cities*

	Documentation	Lecturer	Equipment	Curriculum	Simulator specs.	System non-conformities
Antalya	0.336	0.385	0.451	0.333	0.361	0.356
Balıkesir	0.605	1.000	0.356	0.333	0.333	0.385
Çanakkale	0.515	0.680	0.392	0.333	0.333	0.385
Giresun	0.333	0.586	0.434	0.367	0.451	0.385
Mersin	0.688	0.668	0.630	1.000	0.333	0.270
İstanbul	0.433	0.399	0.324	0.395	0.475	0.317
İzmir	0.384	0.359	0.324	0.343	0.352	0.363
Kocaeli	0.712	0.486	1.000	0.359	0.939	0.294
Muğla	0.347	0.368	0.324	0.336	1.000	0.277
Ordu	1.000	0.362	0.324	0.382	0.806	0.311
Rize	0.392	0.443	0.414	0.347	0.390	0.385
Samsun	0.413	0.459	0.347	0.434	0.333	0.385
Sinop	0.356	0.333	0.418	0.333	0.333	0.385
Trabzon	0.367	0.368	0.333	0.384	0.333	0.385

Table 5. *Grey relation coefficient (ε_i) and grey relation ranking (r_j)*

	Documentation	Lecturer	Equipment	Curriculum	Simulator specs.	System non-conformities
ε_i	0.762	0.145	1.137	1.055	0.602	0.338
r_j	3	6	1	2	4	5

Table 6. *Geographical distribution (by cities) of GRA degrees of non-conformities*

	Documentation	Lecturer	Equipment	Curriculum	Simulator specs.	System non-conformities
Antalya	0.044	0.025	0.054	0.077	0.105	0.058
Balıkesir	0.079	0.065	0.042	0.077	0.097	0.062
Çanakkale	0.068	0.044	0.047	0.077	0.097	0.062
Giresun	0.044	0.038	0.052	0.085	0.131	0.062
Mersin	0.09	0.043	0.075	0.231	0.097	0.044
İstanbul	0.057	0.026	0.039	0.091	0.139	0.051
İzmir	0.05	0.023	0.039	0.079	0.103	0.059
Kocaeli	0.094	0.031	0.119	0.083	0.274	0.048
Muğla	0.046	0.024	0.039	0.078	0.292	0.045
Ordu	0.131	0.023	0.039	0.088	0.235	0.05
Rize	0.051	0.029	0.049	0.08	0.114	0.062
Samsun	0.054	0.03	0.041	0.1	0.097	0.062
Sinop	0.047	0.022	0.05	0.077	0.097	0.062
Trabzon	0.048	0.024	0.04	0.089	0.097	0.062

of new training requirements in the STCW-1978 Convention and Code and amendments, known as the Manila 2010 changes. In the audits carried out, it was observed that the knowledge level of the representatives of the institutions and trainers on the STCW-1978 Convention and amendments was very limited. Awareness about the training methodology envisaged in the Convention and the Code was low, and, the education system was structured on the basis of the national legislation. However, Seafarers and Pilots Regulations and the Directive of Seafarers and Pilots Training and Examination do not include all details of the STCW-1978 Convention, the STCW Code and amendments. Lecturers and maritime training and education institutes should be aware of all requirements of the STCW Convention and Code and amendments.

The Directive on Seafarers and Sea Pilots Training and Examination ordered all maritime training and education institutions to reflect the Manila-2010 changes in their curriculum as of July 1, 2013. However, comprehension of these changes, and their inclusion in the curriculum, occurred only as part of the corrective and preventive actions for the non-conformities documented in this category as a result of the audits. Regarding this, the administration requested that the Manila-2010 changes and the STCW Convention and Code comparison chart, which show how the competence, knowledge, understanding, and expertise required in the STCW Code, along with competency measurement methods and evaluation criteria, are reflected in the curriculum, be presented in the audits.

The documentation categories rank third in the GRA coefficient of non-conformity factors. In this category, there are non-conformities arising from not complying with the documentation requirements by the Quality Management System (QMS). When the distribution in this category is examined, it is found that Kocaeli and Ordu share the first place. It is followed by Mersin and Balıkesir. The provinces with the least density in this category are Antalya and Giresun.

The grey relation coefficient of the "Simulator Specifications" category was calculated as 0.602. Empirical results show that factors with a degree of grey relationship higher than 0.5 are highly effective as indicators for warnings for maritime education institutions, so these factors should also be carefully considered. In this category, Kocaeli and Muğla were identified as the provinces with the highest values. Then Ordu and Samsun provinces comes.

With the developing technologies, the number of simulator-based training has increased in many fields. In simulators with enhanced reality, trainees or students can carry out practical training on scenarios and gain experience for the profession. However, high simulator costs, trainee/student limitation per simulator, and restriction on common use of simulators between training institutions bring additional costs to training institutions. Also, due to rapid changes in simulator technologies, software updates, maintenance, and repair costs of simulators have a significant share in the budget. When all these facts are evaluated together, it can be said that there is an inverse relationship between the degree of the non-compliance factor in this category and the financial strength of the institution.

There are two categories with a grey relation coefficient less than 0.5. These categories are "System Non-conformities" and "Lecturer". Considering that these two categories were strictly inspected during the initial authorization of maritime training institutions, and those who could not meet the conditions were not authorized, training institutes pay much attention to these categories. This attention is reflected in the results.

In the category of "System Non-conformities" the density of the GRA coefficient follows the order of Çanakkale, Balıkesir, Sinop, Samsun, Giresun, Trabzon and Rize. Considering the distribution of training institutions in these provinces, it can be concluded that the number of high schools and private courses is substantial. It can be concluded that the implementation of the QMS in high schools and private courses is relatively weak compared to higher education institutions.

Distribution of non-compliance factors according to the "Lecturer" category follows the order of Balıkesir, Çanakkale, and Mersin. Considering the distribution of training institutions in these provinces, the non-conformities are observed to be the non-conformities in the lecturer category are also concentrated in high school and private training institutions.

Due to the restriction on the number of figures, only 2 selected maps are included in this article, one of which

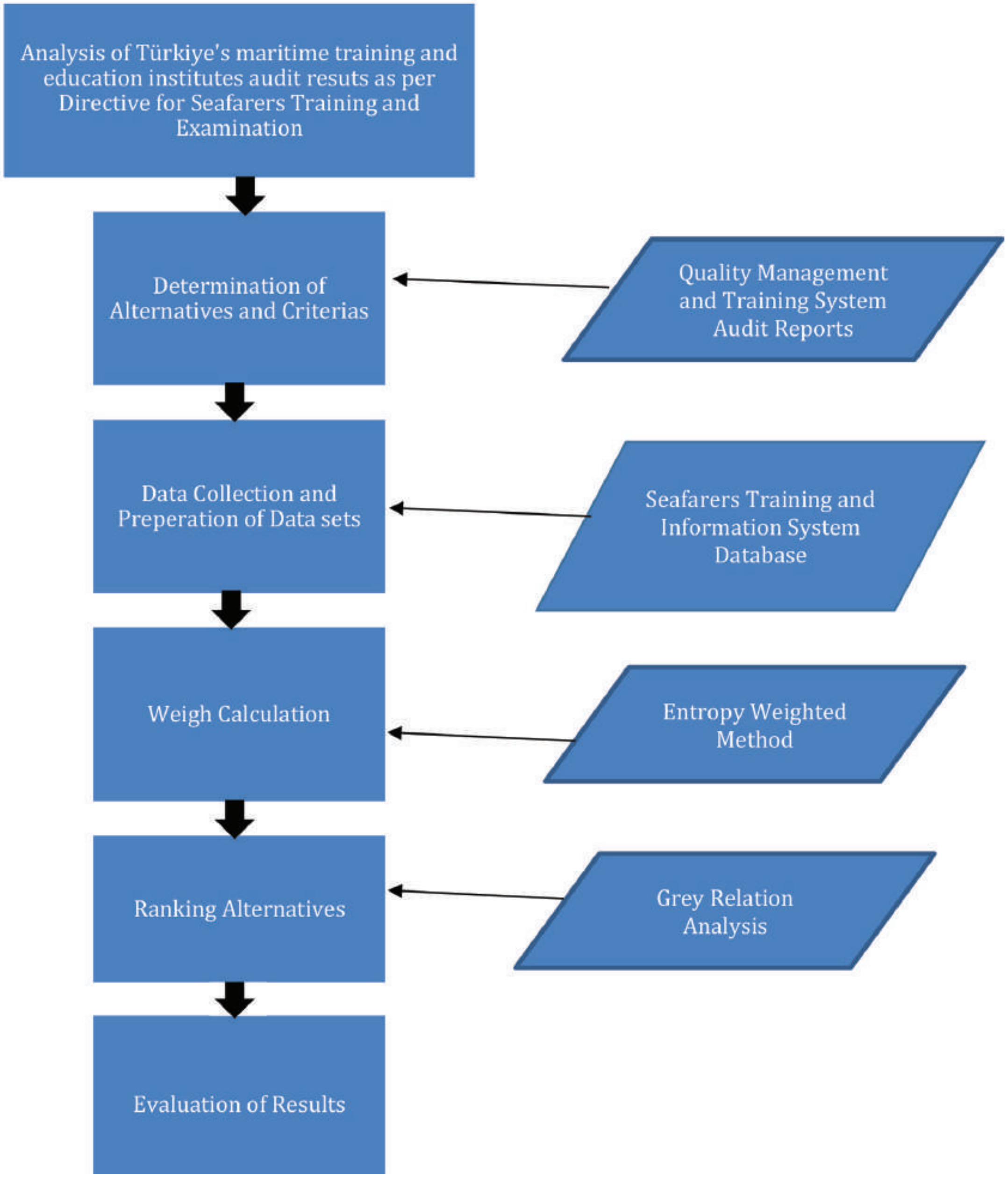

Figure 1. *Methodological framework of analysis of Türkiye's maritime training and education institutes audit results as per Directive for Seafarers Training and Examination*

shows all non-conformities in a single map (Figure 2), and the total coefficient of Entropy Weighted GRA Analysis geographical distribution is given in Figure 3.

In QGIS demonstration of the GRA results, the Equipment category map is selected as the base chart, since it has the highest GRA coefficient and other categories are also shown in pie charts. The legends of the maps were automatically created because the numbers within the range of coefficients were close. Densities of the non-conformities are displayed in order where higher density is darker.

In Figure 2, Kocaeli and Mersin, which have the highest non-conformity factor in the equipment category on the map, also have high GRA coefficients in curriculum and simulator specifications categories.

Figure 3 shows the distribution of maritime education institutions, according to GRA factors of total non-conformity. In the quality assessment of institutions: considering the total non-conformity factor as an appropriate method includes all non-conformities together in the analysis, since the weight of each invoice is included. According to the results of this analysis, the highest total non-conformity distribution was seen in Mersin, Kocaeli, and Ordu. These provinces were followed by Muğla, Balıkesir, Trabzon and İstanbul.

İstanbul, which has a total of 41 maritime education institutions, 26 of which are accredited, ranks 7th in terms of total non-compliance factors. Türkiye's center of maritime industry stakeholders accepted involved being involved to a large extent with the oldest training institutions in İstanbul. The perception of hosting the best maritime training institution does not coincide with the results obtained. These results show that training institutions in İstanbul have correctable and improvable weaknesses.

In Antalya, Trabzon, and Samsun, which are included in the map, the non-conformity factor has been assigned relatively less weight. These provinces are followed by Rize. The best results in distribution according to total non-conformity factors were obtained in Sinop and İzmir.

Comparing the distribution of non-conformity categories and the distribution of total non-compliance factors of training institutions according to all categories, it was determined that the distribution of total non-compliance factors does not always coincide with the provinces with the highest non-compliance weight. For example, Muğla province is one of the provinces with the lowest density in the equipment category, which has the highest degree of relation, while it is one of the densest provinces in the distribution of total non-compliance factors.

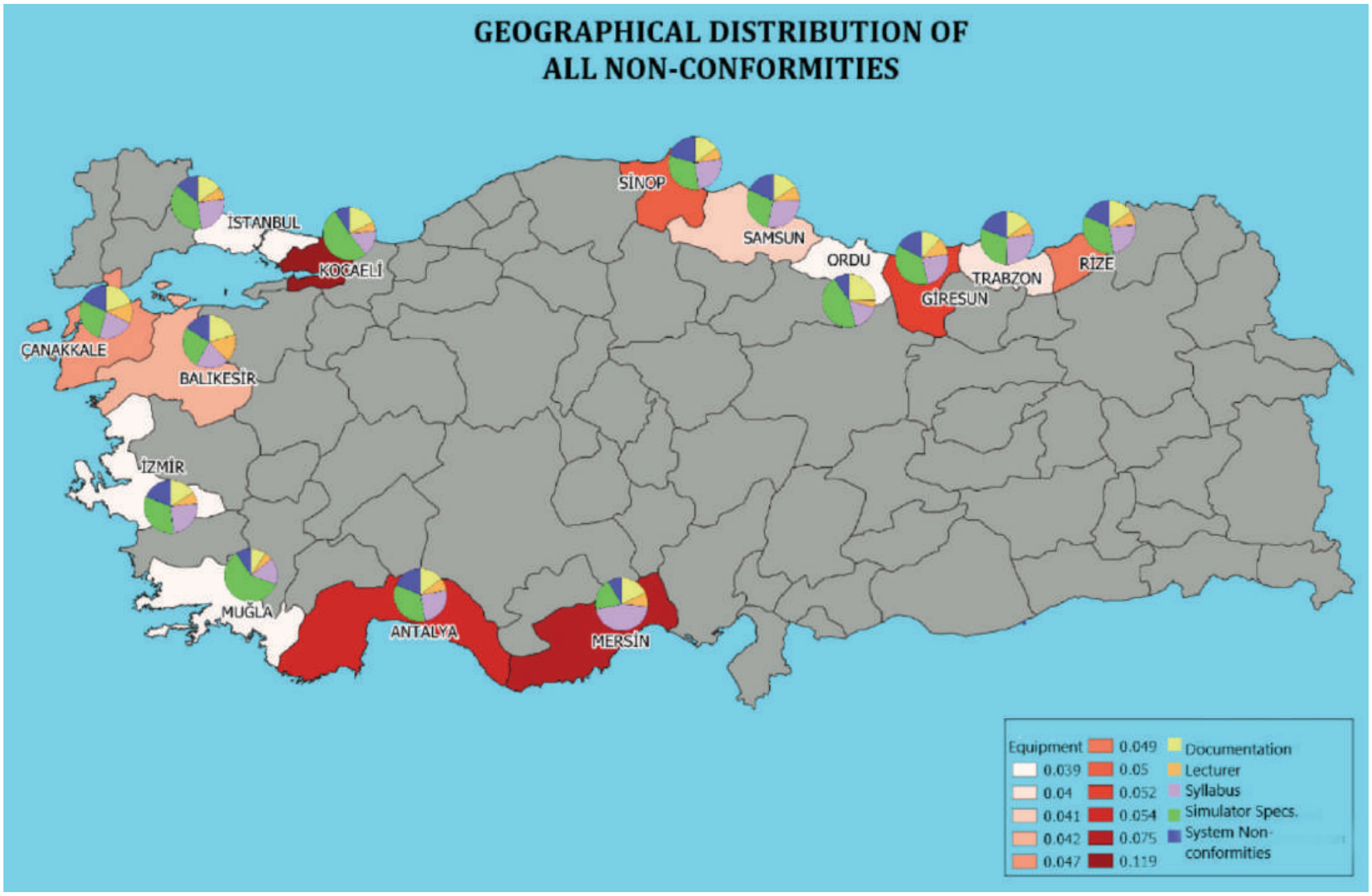

Figure 2. *Non-conformities distribution of all categories*

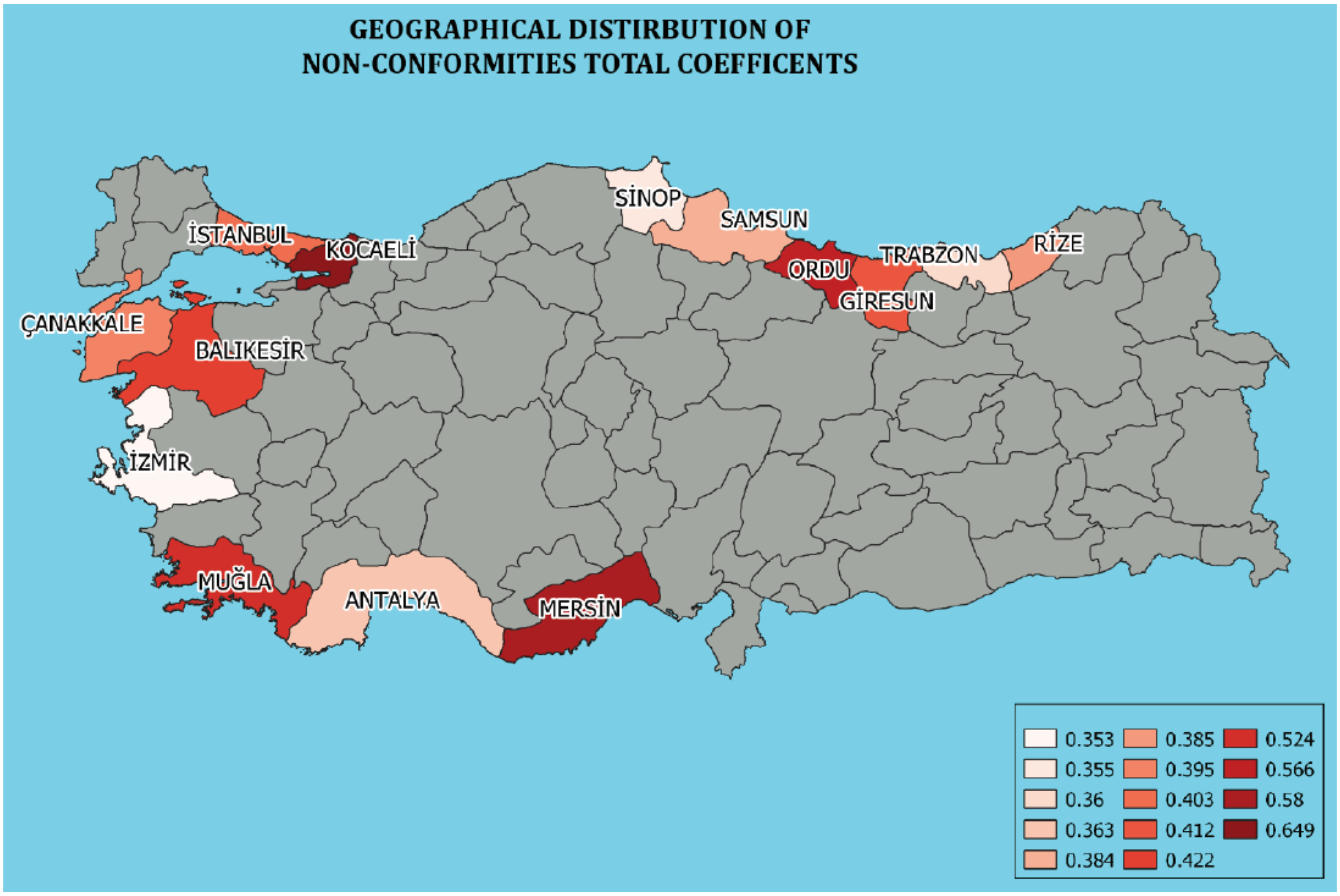

***Figure 3.** Non-conformities distribution of total GRA coefficients*

GRA: Grey Relation Analysis

5. Conclusion

Quality assessment of higher education institutes is an attractive subject for researchers, and many studies have been carried out, with numerous quality measurement scales developed. However, common shortcomings of these scales are the lack of objectivity in the criteria, and most of these scales are based on questionnaires. No study has been found analysing the results of findings of audits carried out by third parties, which can provide a more objective assessment of the training institute.

Different factors and criteria can be selected for quality assessment of training facilities. Physical facilities, reliability and security, sensitivity/empathy, fees, academic staff, transport facilities and infrastructure are the most commonly used criteria in research. However, in scales developed in recent years, new criteria such as academic attendance, cognitive attendance, training quality, academic staff profiles, curriculum, infrastructure, and facilities have become main measurements in these scales. Nevertheless, the common specification of these scales is mostly subjective and based on questionnaires.

Also, results of these assessments can be useful in many ways, including the concentration of non-conformity categories, their root causes, and their geographical distribution.

In this study, entropy weighted GRA of audits done in accordance with the Directive of Seafarers Training and Examination results of maritime training and education institutes is carried out, and results are reflected in GISs. The outcome of the study reveals Türkiye's Maritime Training Institutions non-conformities map, thus, serving as an indicator of their quality relative to their geographic distribution.

Analysis results show that the effect of the non-conformities categories, that are reflected as GRA coefficients, is in the following ranking: Equipment (1.137); Curriculum (1.055); Documentation (0.762); Simulator Specifications (0.602); System Non-conformities (0.338); and Lecturer (0.145). These weighted coefficients are applied to non-conformities segmented by geographic distribution of maritime training and education institutes, and results are reflected with the help of the GIS.

Because returning the highest equipment category returns the highest GRA coefficient along with the root causes, resource management of the maritime training institutes needs to be improved. However, legislation and administrative requirements limit the common use of training facilities, and in most cases, equipment is used only for a very limited period of the year, and remains idle for the rest, which can be interpreted as ineffective resource management. The same conclusions can be made for simulators.

Curriculum, which yields the second highest coefficient, should follow both national and international legislation, mainly STCW Convention and STCW Code and amendments, and should have uniform implications. Administration or Higher Education Board can provide draft curriculum to avoid any discrepancies between training institutions.

Documentation results show the culture and familiarity with QMS, and in order to establish a well-functioning QMS, dedicated personnel with relevant training should be assigned as Quality Coordinator with sufficient authority.

The result of the study can be helpful to both maritime training and education institutes and administrations to minimize the categories of non-conformities and improve their training quality.

Ethics

Ethics Committee Approval: For the study, data usage permission was obtained from the Ministry of Transport, Maritime Affairs and Communications, General Directorate of Sea and Inland Waters Regulation (approval no.: 51056, date: 18.08.2017).

Footnotes

Authorship Contributions

Concept design: E. Güzel, Data Collection or Processing: E. Güzel, and P. Bolat, Analysis or Interpretation: E. Güzel, and P. Bolat, Literature Review: E. Güzel, Writing, Reviewing and Editing: E. Güzel.

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Examination of Failures in the Marine Fuel and Lube Oil Separators Through the Fuzzy DEMATEL Method

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Abstract

Separators are essential equipment on ships, regardless of the vessel type or the type of engine installed, whether the main, and auxiliary engines are two-stroke or four-stroke. The primary function of these separators, apart from the bilge separator, is to ensure clean fuel delivery to the main engine and auxiliary machinery by removing water and solid contaminants from the fuel. The efficiency of the separators and the level of maintenance they receive directly influence the performance of the ship's machinery, reducing the likelihood of malfunctions and power loss in systems dependent on clean fuel. However, since separators operate at high speeds using centrifugal force and are composed of numerous intricate components, they are prone to potential failures if not properly maintained. While preparing for this study, four experts were asked about the effects of failures that may occur in the separators. According to the criteria received, the fuzzy DEMATEL method, a multi-criteria decision-making method, was used to evaluate the effects of failures. When the results are examined, the most effective factors are the wear of the bearings, contamination, incorrect assembly of the bowls, and bending of the shaft. It is extremely important to have spare parts available on the ship and to maintain the equipment with sufficient authorized crew.

Keywords: Failure, Fuzzy, DEMATEL, Multi-criteria decision making, Separator

1. Introduction

Separators are designed according to basic physics rules and operate on the principle of separating two liquids that don't mix owing to the density difference [1]. Separators are used to separate liquid mixtures with different densities, such as milk and cream [2]. In this context, separators are used in milk processing plants, oil refineries, and ships to separate the input product from desired outputs and other particles. The working principle is to separate the water and solids in the fuel or oil using the centrifugal force of the system rotating at approximately 7000-9000 rpm. Normally, water and solid particles can be separated over time in fuel storage and settling tanks in ships, owing to density differences. However, because ships are exposed to constant movement, it is not possible for sedimentation to occur in a uniform manner. The importance of separators has emerged at this point. Regardless of how heavily contaminated the fuel is, the separator separates the fuel from water and solid particles in line with its operating principle [3]. Separators are divided into two types, purifiers and clarifiers, based on their working method and structure. While clarifier-type separators have a single outlet for only fuel, purifiers have two outlets for both water and fuel [4,5]. If separators are not used effectively and if their maintenance is not performed on time and as required, particles in the fuel will move towards the equipment using that fuel. Fuel will move towards equipment, which may cause damage to fuel pumps, injectors, and injector nozzles, and cause a decrease in the performance of the machines. This is because uncleaned fuel in the injector damages it and causes poor combustion [6,7]. Therefore, the importance of the fuel system is better understood, particularly for ships that are constantly sailing.

Marine separator systems are designed to separate and clean fuel and oil types such as marine diesel oil, heavy fuel oils

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with a maximum CST of 600, detergent lubricants, very low sulphur fuel oil, ultra-low sulphur fuel oil, and distillate fuels. The parts required for the separation system, shown in Figure 1, are the separator, control unit, valves, heating system, and feed pump. The general flow is dirty or used oil/fuel inlet from A, if it needs to be pumped and heated; oil/fuel circulation from C; water inlet from D; sludge or water outlet from E; and, after passing through pressure switches, cleaned oil/fuel outlet from B.

Many accidents occur on ships, causing environmental pollution, fires, and even death, depending on various factors [8]. When accidents are specifically examined in terms of environmental impact, one of the most important causes of accidents is an inability to perform efficient maneuvers owing to the main engine power loss. One of the reasons for the power loss of the main engine is damage to the injectors and fuel pumps due to the lack of clean fuel [9]. Failures are caused by both fuel issues and maintenance not being carried out at the times specified by the manufacturers [10]. Failure to maintain separators in a timely manner and by competent crews causes many accidents, financial losses, and equipment damage [11,12]. In addition, because separators operate at very high speeds, maintenance, performed by unqualified crews, causes serious accidents to seafarers quickly, resulting in death [3]. Ships have a service life, just like living organisms have a life span. Regular maintenance of equipment and replacement of required parts at the times specified in maintenance books will extend the life of the equipment. A longer lifespan of a ship can be achieved through regular maintenance [13]. Generally, separator failures consist of three main components. The first one is a mechanical function error (vibration, sound, odor, low speed, etc.), the second one is a separation function fault (insufficient separation, insufficient sludge output, bowl opening during operation, etc.), and the third one is a vibration switch failure (difficulty reactivating the vibration electric switch). The faults are specified here: they can be described as dirty separator bowl, shaft curvature, bearing deformation, filter pollution, and insufficient fuel and oil supplied to the separator [14].

This study investigated the general situation of failures, the spares that should be available on the ship, the importance of maintenance performed by authorized persons, and the determination of the root causes of the failures. Additionally, it examined the benefit of using the multi-criteria decision-making (MCDM) method to counter possible failures, thereby enhancing the longevity and performance of the equipment. MCDM methods are statistical tools used in complex decision-making processes where multiple factors need to be evaluated. These methods aim to rank or choose among alternatives based on different evaluation criteria. The development of MCDM methods began with the introduction of various approaches in the mid-20th century. These methods continue to be developed by considering the decision-making process in a broader context, including technologies such as artificial intelligence and machine learning [15]. Fuzzy-logic-based methods can be especially effective in cases of uncertainty and imprecise information. Methods such as fuzzy DEMATEL, fuzzy TOPSIS, fuzzy PROMETHEE, and fuzzy VIKOR can help in making better decisions by handling uncertainty and multiple criteria in complex decision-making processes [16,17]. Each method has advantages and disadvantages, and the choice of method may vary depending on the problem context, data situation, and user preferences. Expertise is required to effectively use these methods, and careful analysis is essential to obtain accurate results. Fuzzy DEMATEL helps to handle data containing uncertainty more effectively than other MCDM methods; therefore, it is more suitable for complex systems such as fault detection [18]. Fuzzy-logic-based MCDM methods are widely used in various fields. To provide some examples of these studies, such methodologies are employed in the detection of skin cancer in the medical field [19], in the diagnosis of cattle diseases in the veterinary field [20], in dryer oven systems in the food sector [21], and in the field of social life in individual emotion analysis [22].

Current examples of usage areas are abundant in open literature, including conference proceedings and scientific articles. This study will share information on ship-specific studies and some of the publications examined in this context are as follows. Tamer et al. [23] investigated MCDM applications in postgraduate theses and journal papers for Turkish naval architecture and marine engineering area. Tuncel et al. [24] applied a Quadratic Mean fuzzy AHP

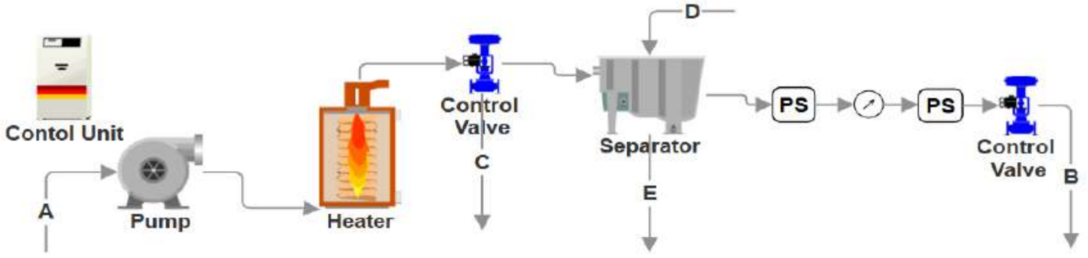

***Figure 1.** Marine seperator system [3]*

method to the preparation steps of electronic nautical charts for navigation, to identify probable risks. The hybrid fuzzy AHP-TOPSIS method, applied by Demirel [25], was used for selecting a roll motion stabilizer to reduce the roll motion of a fishing boat. The study was conducted by Erol [26] to determine the ship type to be built in shipyards in Turkey using fuzzy TOPSIS and fuzzy VIKOR methods. A new fuzzy TOPSIS method based on global fuzzy sets was used by Demirel [27] to select a stabilizer that directly affects many criteria, such as comfort, safety, and speed of passenger ships. Wang et al. [28] made a risk assessment based on advanced fuzzy multiple criteria such as MULTIMORA, AHP, and Monte Carlo simulations for fires occurring in the engine room of ships. Madi et al. [29] examined the prominent criteria in the selection of ports where ships call for different purposes using the fuzzy decision-making method on the Malaysian example. Jianping et al. [30] optimized ship main dimensions and main engine power using fuzzy decision-making theory, considering economic data. Risk analyses were carried out by Ceylan [31] employing failure mode and effect analysis for high-pressure air systems, which are critical to safely preventing accidents and ensuring ship operations.

Bashan and Demirel [32] evaluated the critical operational faults of marine diesel generators using the DEMATEL method, to detect relationships between faults. Bucak et al. [33] presented strategies created using the fuzzy AHP method to prevent ship-borne emissions in the strait of Istanbul. Balin et al. [34] explained the reasons for the failures occurring in the auxiliary systems of the ship's main engine, their effects on the system, and their degree of severity with the fuzzy DEMATEL method. Failure modes, effects, and criticality analysis were carried out by Ahmed and Gu [35] using the fuzzy logic method, based on empirical and statistical data regarding boiler failures that cause loss of life, health problems, and large-scale material damage on ships. Yucesan et al. [36] examined the failures of ship diesel generators by evaluating them with the best-worst method based on fuzzy logic. Marichal et al. [37], a new approach for the predictable maintenance of separators was presented in using a Genetic Neuro-Fuzzy System. Bashan et al. [38] used the fuzzy logic-based best-worst method to examine the 20 most critical failure types, frequently seen in ship heavy fuel oil separators.

It is important that the fuel and oil separators used on ships are maintained and operated according to their working principles. If the oil separator cannot adequately separate water and waste oil from the oil, rapid wear may occur in the bearings of the main engine and auxiliary generator, which may prevent the completion of the journey. Fuel that has not been purified by separators is delivered from the service fuel tank to the fuel pump, passing through a filter before being sent to the main engine and auxiliary generator. Any unrefined fuel that traverses the filter can carry particulates, which may inflict damage on the fuel pumps and injectors, thereby hindering the required power output. Therefore, maintenance of separators on ships is of great importance. One of the main motivations of this study is that the fuzzy DEMATEL method has not been used before to perform an analysis with a similar number of faults. In this study, guided by expert opinions, 20 types of failures frequently seen in the fuel and oil separators used on ships were identified, and the effects and importance of these failures on each other were analyzed by applying the fuzzy DEMATEL technique.

2. Research Method

2.1. Fuzzy Logic and Fuzzy Set

In classical logic, until recently, belonging was a concept that was usually measured and evaluated from 0 to 1. However, there may not always be clear values, such as zero and one; preferences and importance orders may come into play and tell us the possibilities. Therefore, a fuzzy logic evaluation was performed by Zadeh [39].

Triangular fuzzy numbers can be represented as (a1, a2, a3), as shown in Figure 2 [27], and the function of the fuzzy number $\tilde{A}$ is specified in Equation 1. Fuzzy numbers show small, medium, and large probabilities.

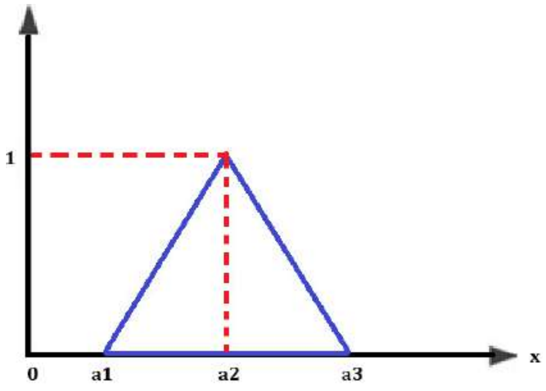

Figure 2. *Triangular fuzzy numbers*

$$f_{\tilde{A}}(x) = \begin{Bmatrix} 0, \ x < a1 \\ \frac{(x-a1)}{(a2-a1)}, \ a1 \leq x \leq a2, \\ \frac{(a3-x)}{(a3-a2)}, \ a2 \leq x \leq a3, \\ 0, \ x > a3 \end{Bmatrix} \tag{1}$$

$\tilde{A}$ and $\tilde{B}$ are determined as (a1, a2, a3) and (b1, b2, b3), the operation to be performed between them is as in Equations 2-5;

$$\tilde{A}(+)\tilde{B} = (a_1, a_2, a_3)(+)(b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \tag{2}$$

$$\tilde{A}(-)\tilde{B} = (a_1, a_2, a_3)(-)(b_1, b_2, b_3) = (a_1 - b_1, a_2 - b_2, a_3 - b_3) \tag{3}$$

$$\widetilde{A}(\times)\widetilde{B} = (a_1, a_2, a_3)(\times)(b_1, b_2, b_3) = (a_1b_1, a_2b_2, a_3b_3) \quad (4)$$

$$\widetilde{A}(\div)\widetilde{B} = (a_1, a_2, a_3)(\div)(b_1, b_2, b_3) = (a_1/b_1, a_2/b_2, a_3/b_3) \quad (5)$$

Normalization of fuzzy numbers using the "crisp score" method $\widetilde{\varpi}_{ij}^{k} = \left(a_{1ij}^{k}, a_{2ij}^{k}, a_{3ij}^{k}\right)$ shows the impact of criterion i on criterion j based on expert opinions. Normalization, Equation 6-9;

$$xa_{1ij}^{k} = \left(a_{1ij}^{k} - \min a_{1ij}^{k}\right)/\Delta_{\min}^{\max} \quad (6)$$

$$xa_{2ij}^{k} = \left(a_{2ij}^{k} - \min a_{2ij}^{k}\right)/\Delta_{\min}^{\max} \quad (7)$$

$$xa_{3ij}^{k} = \left(a_{3ij}^{k} - \min a_{3ij}^{k}\right)/\Delta_{\min}^{\max} \quad (8)$$

$$\Delta_{\min}^{\max} = \max r_{ij}^{n} - \min l_{ij}^{n} \quad (9)$$

Left (ls) and right (rs) normalized values, Equations 10 and 11;

$$xls_{ij}^{k} = xa_{2ij}^{k}/\left(1 + xa_{2ij}^{k} - xa_{1ij}^{k}\right) \quad (10)$$

$$xls_{ij}^{k} = xa_{3ij}^{k}/\left(1 + xa_{3ij}^{k} - xa_{2ij}^{k}\right) \quad (11)$$

Calculation of Crisp values, Equation 12 and 13;

$$x_{ij}^{k} = \left[xls_{ij}^{k}\left(1 - xls_{ij}^{k}\right) + xrs_{ij}^{k} \times xrs_{ij}^{n}\right]/\left(1 - xls_{ij}^{k} + xrs_{ij}^{k}\right) \quad (12)$$

$$\widetilde{\varpi}_{ij}^{k} = \min a_{ij}^{n} + x_{ij}^{n}\Delta_{\min}^{\max} \quad (13)$$

Integrating the surveys conducted by k experts (14),

$$\widetilde{\varpi}_{ij}^{k} = 1/k\left(\widetilde{\varpi}_{ij}^{1} + \widetilde{\varpi}_{ij}^{2} + \ldots + \widetilde{\varpi}_{ij}^{k}\right) \quad (14)$$

2.2. Fuzzy DEMATEL Method

The DEMATEL method is a powerful technique for elucidating cause-effect relationships and interdependencies within complex systems, which offers a suitable approach to unraveling this complexity. By assigning not only weights to criteria but also quantifying their interrelationships, DEMATEL provides a more comprehensive analysis. Furthermore, its visual representation of intricate relationships enhances understanding and facilitates the interpretation and communication of findings to decision-makers.

In this method, the problems are first determined, the relationship coefficients between these problems are assigned, necessary matrices are calculated, and their graphs are drawn. The most important thing here is that determination of problems and assignment of coefficients are done by experts. For this purpose, various fuzzy DEMATEL methods have been proposed using the fuzzy set approach. In this study, instead of coefficients 0, 1, 2, 3, and 4, coefficients (0.0, 0.0, 0.25), (0.25, 0.50, 0.75) were used, as shown in Table 1 [29].

Table 1. Fuzzy scale

Linguistic expressions	Triangular fuzzy numbers
Little effective	(0.00; 0.00; 0.25)
Less effective	(0.00; 0.25; 0.50)
Normal effective	(0.25; 0.50; 0.75)
Very efficient	(0.50; 0.75; 1.00)
Too effective	(0.75; 1.00; 1.00)

The selection of triangular fuzzy logic within the DEMATEL method offers significant advantages due to its computational efficiency, simplicity, and ability to address uncertainty in expert assessments. Triangular fuzzy numbers provide a structured yet flexible means of representing subjective judgments, effectively capturing variations in expert opinions while maintaining a relatively low computational burden. Their linear nature facilitates both interpretation and application, making them particularly suitable for decision-making scenarios where precise numerical values are difficult to obtain. Furthermore, utilizing Excel for the crisp score method enhances accessibility and ease of implementation, enabling efficient analysis while preserving methodological rigor. This integration strengthens the reliability and interpretability of the DEMATEL method, ensuring its applicability across diverse domains [40].

During the analysis, four experts who gained experience by working as oceangoing chief engineers on different types of ships, were asked to give their opinions about separator failures and to determine the importance of these failures. Each of the experts whose opinions were received has 10 or more years of experience. The first expert has twelve years of experience as a chief engineer, the second expert has twenty-eight years of experience as a chief engineer, the third expert has five years of experience as a chief engineer and ten years of experience as a separator service engineer, and the fourth expert has seven years of experience as a chief engineer and six years of experience as a machine inspector. Figure 3.

In the third step, a direct relationship matrix A = n×n is created by using triangular fuzzy numbers and comparing the factors, as shown in Equation 15. It also T_{ij} indicates the degree to which factor i affects factor j.

$$A = \left[t_{ij}\right]_{n\times n} \quad (15)$$

Subsequently, based on the direct relationship matrix A, the normalized relationship matrix S is determined by the

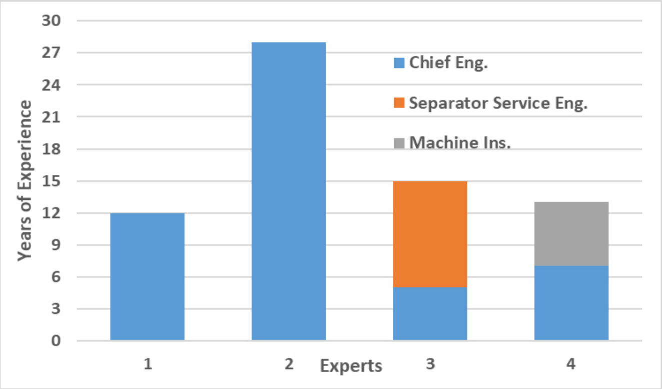

Figure 3. Years of experience of experts

following calculation: (k experts) Equations 16 and 17 in the fourth step.

$$S = k \times A \tag{16}$$

$$k = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} aij} \tag{17}$$

In the fifth step, the total relationship matrix T is obtained through the operation of the normalized relationship matrix S with identity matrix I, as given by Equation 18.

$$T = S\,(I - S)^{-1} \tag{18}$$

In the sixth step, the D and R vectors are obtained by adding the rows and columns in the total relationship matrix: Equations 19-21. To create a cause-effect graph, (D-R) and (D + R) vectors must be placed on a graph. In this graph, the horizontal axis D+R indicates “Importance” and the vertical axis D-R indicates “Relationship.” If D-R is greater than 0, it indicates a particular outcome; if it is less than 0, it suggests a different result.

$$T = \left[t_{ij}\right]_{n\times n},\ i,j=1,2,\ldots,n. \tag{19}$$

$$D = \left[\sum\nolimits_{i=1}^{n} t_{ij}\right]_{1\times n} = \left[t_i\right]_{n\times 1} \tag{20}$$

$$R = \left[\sum\nolimits_{j=1}^{n} t_{ij}\right]_{1\times n} = \left[t_j\right]_{n\times 1} \tag{21}$$

Finally, the importance weights are calculated by applying the obtained D and R values to Equations 22 and 23 in the seventh step.

$$w_i = \left\{\left(\tilde{D}_i^{def} + \tilde{R}_i^{def}\right)^2 + \left(\tilde{D}_i^{def} - \tilde{R}_i^{def}\right)^2\right\}^{\frac{1}{2}} \tag{22}$$

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{23}$$

3. Results and Discussion

Experts’ opinions were sought to explain the reasons for the 20 selected faults. When the fault notification section of the separator is examined, more faults can be seen. However, experts agree that these faults are interconnected. For example, if the electric motor that enables the separator to operate does not receive any electricity (the cable may be broken), this is not considered a fault caused by the operation of the separator. However, if the electric motor does not receive electricity at the correct frequency, the separator will initially operate for a short time, but then the motor will burn out. Consequently, the separator will not operate properly and, eventually, cause it to fail.

For some other cases, experts’ opinions are as follows. The maximum bending distance of the separator shaft is 0.04 mm. If this shaft bending remains unnoticed, because the vibration occurring during the operation of the separator will cause the lower and upper bearings that support the shaft, or the rubber buffers connected to the upper bearing and the lower bearing, to deteriorate. These situations actually trigger each other. It is not known whether the real failure is due to the bending of the separator shaft or the deterioration of one of the upper or lower bearings. Since it is equipment consisting of parts that frequently interact and are interconnected, the root causes of failures in machines such as separators are not easily determined. In line with the most experienced events, the root causes of the most frequently encountered failures have been identified. To determine the parts and elements that cause or may cause failure in separators based on manufacturer manuals and expert experiences, the 20 factors in Table 3 can be identified [3].

Table 2. *DEMATEL method analysis steps*

Step	Definition
1	Determining the purpose of the problem and establishing the decision group
2	Determination of criteria and creation of fuzzy scales
3	Decision makers evaluate the bilateral relationships between factors and create a direct relationship matrix
4	Creation of normalized direct relationship matrix
5	Creating the total relationship matrix
6	Creating the impact-factor graph
7	Calculation of importance weights

Table 3. *Possible separator failures [3]*

C1	Wear or lubrication of friction elements	C11	Bowl shaft bending
C2	Belt tension is too weak or it is slipping	C12	Overheating, wear of the upper and/or lower bearing
C3	Electric motor failure	C13	Defect of shaft upper bearing rubber damper
C4	Incorrect energy supply	C14	Unbalanced waste sediment within the waste area
C5	Bearing deformation or wear	C15	Very low oil level in oil tank
C6	50 Hz pulley powered by 60 Hz power supply	C16	Incorrect power transfer or frequency supply
C7	High position of paring disc incorrect	C17	Bowl does not close or leaks
C8	Bowl imbalance**	C18	Bowl casing drain obstructed
C9	Height adjustment of paring disc is incorrect	C19	Upper bearing leak
C10	Vibration dampers in frame feet worn out	C20	Condensation

The total number of failures identified was 20, and details such as poor cleaning, improper assembly, insufficient disc, bowl tightness, and incompatibility of separator parts were stated for C8 Bowl imbalance (**). At the end of the evaluations, four matrices were obtained and converted from linguistic expressions into fuzzy number matrices, as shown in Table 4. Each expert created the matrices, which are presented as real examples in Table 3, by determining the degree of influence of the criteria on each other using the triangular fuzzy scale in Table 1.

In line with the information provided by the experts, a 20 × 20 matrix was created, and solutions were derived by applying Equations 9, 11, 12, 13, and 14. The direct-relationship matrix in Table 5, was created by averaging the values.

In the fourth step, the normalized direct relationship matrix in Table 6 was formed as a result of calculations 2 and 3, using the direct relationship matrix.

The normalized relationship matrix was processed with the number four, and the Table 7 was established.

When formulas 5, 6, and 7 were applied to the total relationship matrix, the D, R, D+R, and D-R values were shown in Table 8.

Using the values in Table 8, the (D+R)-(D-R) cause-effect factor relationship graph is shown in Figure 4. It can be seen that C1, C5, C8, C10, C11, C12, C13, C19, and C20, which have the highest D+R value above 0, are of the highest importance. It is observed that the D+R values remaining above zero have the highest value and importance. To mention these, C5 "bearing damage or wear", C12 "upper and/or lower bearing overheated, damaged or worn", C11 "bowl shaft bending", C8 "bowl imbalance", C13 "shaft upper bearing rubber damper defect", C18 "bowl casing drain obstructed", C10 "vibration dampers in frame feet worn out", C19 "upper bearing leakage", and C16 "incorrect power transmission or frequency supply (50/60 Hz)". As can be seen, bearing wear is of the highest importance. C5 is considered bearing wear. C12 is considered to be the wear of one of the upper or lower bearings, and it indicates that the bearing for the shaft has started to weaken. C11 shows that the bearings have started to deteriorate due to the bending of the shaft. Since more force will be created in the bearings due to the centrifugal effect because of the high-speed rotation of the shaft, the bearings will start to deteriorate. C8, bowl imbalance, is caused by inadequate and improper separator maintenance. Therefore, the separator will operate with excessive vibration, will not be able to perform sufficient separation, and will wear the bearings and cause failure. C13 identifies a defect in the shaft upper bearing rubber damper. Due to the loss of the rubber damper feature, the separator will start to wear the upper bearing, resulting from the hard closing of the bowl caused by the opening and closing of water while the solid waste and water outlet is discharged. Eventually, it will wear the lower bearing and cause the shaft to bend. C18: The bowl casing drain is obstructed due to the blockage of the solid waste and water outlet of the separator. Consequently, the amount of used oil/fuel in the bowl will increase as it cannot clean

Table 4. *Fuzzy number matrices*

	C1	C2	C3	…	C18	C19	C20
C1	(1.00;1.00;1.00)	(0.50;0.75;1.00)	(0.50;0.75;1.00)	…	(0.00;0.25;0.50)	(0.50;0.75;1.00)	(0.00;0.00;0.25)
C2	(0.00;0.00;0.25)	(1.00;1.00;1.00)	(0.00;0.25;0.50)	…	(0.25;0.50;0.75)	(0.25;0.50;0.75)	(0.25;0.50;0.75)
C3	(0.00;0.00;0.25)	(0.00;0.00;0.25)	(1.00;1.00;1.00)	…	(0.00;0.00;0.25)	(0.00;0.00;0.25)	(0.00;0.00;0.25)
…	…	…	…	…	…	…	…
C18	(0.00;0.25;0.50)	(0.00;0.00;0.25)	(0.00;0.00;0.25)	…	(1.00;1.00;1.00)	(0.50;0.75;1.00)	(0.50;0.75;1.00)
C19	(0.00;0.00;0.25)	(0.00;0.00;0.25)	(0.00;0.00;0.25)	…	(0.00;0.00;0.25)	(1.00;1.00;1.00)	(0.50;0.75;1.00)
C20	(0.00;0.00;0.25)	(0.00;0.00;0.25)	(0.00;0.00;0.25)	…	(0.00;0.00;0.25)	(0.00;0.00;0.25)	(1.00;1.00;1.00)

Table 5. *Direct relationship matrix*

	C1	C2	C3	…	C18	C19	C20
C1	1.00	0.57	0.51	…	0.71	0.97	0.00
C2	0.00	1.00	0.21	…	0.36	0.29	0.64
C3	0.16	0.28	1.00	…	0.00	0.00	0.00
…	…	…	…	…	…	…	…
C18	0.21	0.00	0.00	…	1.00	0.97	1.02
C19	0.00	0.00	0.00	…	0.00	1.14	1.02
C20	0.00	0.00	0.00	…	0.00	0.00	1.90

Table 6. *Normalized direct relationship matrix*

	C1	C2	C3	…	C18	C19	C20
C1	0.10	0.05	0.05	…	0.02	0.09	0.00
C2	0.00	0.10	0.02	…	0.03	0.03	0.06
C3	0.02	0.03	0.10	…	0.00	0.00	0.00
…	…	…	…	…	…	…	…
C18	0.02	0.00	0.00	…	0.10	0.09	0.10
C19	0.00	0.00	0.00	…	0.00	0.11	0.10
C20	0.00	0.00	0.00	…	0.00	0.00	0.18

itself sufficiently. Therefore, the separator will first work with the increased oil/fuel, as mentioned, then it will become tightly covered with solid waste, which will cause damage to its bearings. The C10 vibration dampers in the frame feet are worn out. During the first operation of the separator, the adhesion of the friction elements inside the electric motor causes vibration in the separator until its speed stabilizes. Worn-out vibration dampers in frame feet provide a balance by damping this vibration. If the vibration damper is worn out, it will not be able to dampen the vibration during the operation of the separator. It will transmit the centrifugal force on the shaft and bowls to the bearings, causing damage to them. C19 upper bearing leakage is a part of the separator. It is where the bowl part and the shaft part are separated from each other and an O-ring is used as a sealing element. If this O-ring has lost its sealing feature, the used oil/fuel will leak into the shaft part, causing the shaft to slip in the bearings. It may mix with the oil in the chamber where the lower bearing is located, spoil the properties of the oil, or prevent the separator from turning over by causing the belt to become over-lubricated due to excess oil splashing. Regarding issue C16, incorrect power transmission or frequency supply (50/60 Hz), it is important that the electricity supplied to the motor enabling the separator to operate is at the appropriate voltage and frequency. If it is supplied at an incorrect frequency or voltage, even if it operates the separator, it will damage the electric motor, and it will not be able to operate properly.

Table 7. *Total relationship matrix*

	C1	C2	C3	…	C18	C19	C20
C1	0.15	0.11	0.09	…	0.27	0.19	0.20
C2	0.02	0.12	0.04	…	0.34	0.23	0.26
C3	0.03	0.04	0.11	…	0.10	0.10	0.16
…	…	…	…	…	…	…	…
C18	0.07	0.05	0.03	…	0.14	0.19	0.28
C19	0.01	0.01	0.01	…	0.01	0.15	0.14
C20	0.01	0.01	0.01	…	0.00	0.02	0.23

Table 8. *Crisp values*

	D	R	D+R	D-R
C1	1.8	1.2	2.9	0.6
C2	1.0	1.2	2.2	-0.2
C3	0.5	1.0	1.5	-0.5
C4	2.2	0.4	2.6	1.9
C5	1.5	2.6	4.0	-1.1
C6	1.4	0.3	1.7	1.1
C7	0.9	0.1	1.0	0.8
C8	1.7	1.6	3.3	0.0
C9	0.6	0.2	0.8	0.4
C10	0.7	2.2	2.9	-1.5
C11	1.4	2.0	3,4	-0.7
C12	1.2	2.6	3.8	-1.4
C13	1.0	2.2	3.2	-1.1
C14	1.5	1.1	2.6	0.4
C15	0.8	0.2	0.9	0.6
C16	2.4	0.3	2.7	2.1
C17	1.2	1,2	2.4	0.0
C18	1.9	1.0	2.9	1.0
C19	0.7	2.1	2.8	-1.4
C20	0.5	1.6	2.1	-1.1

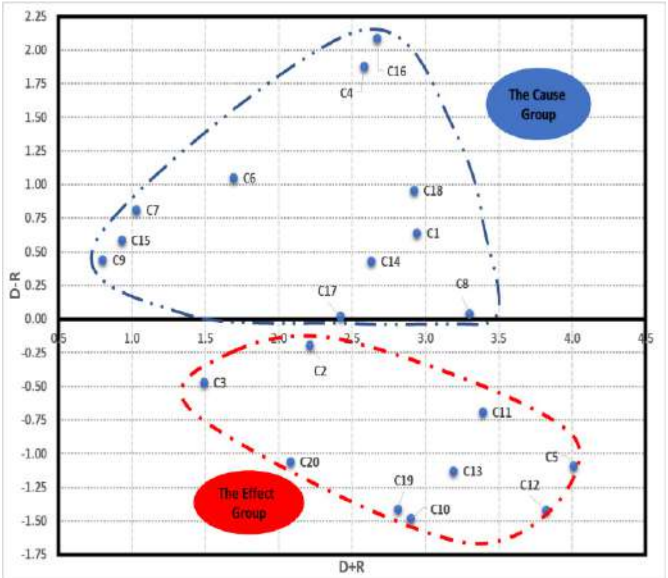

Figure 4. *Cause-effect factors relationship graph*

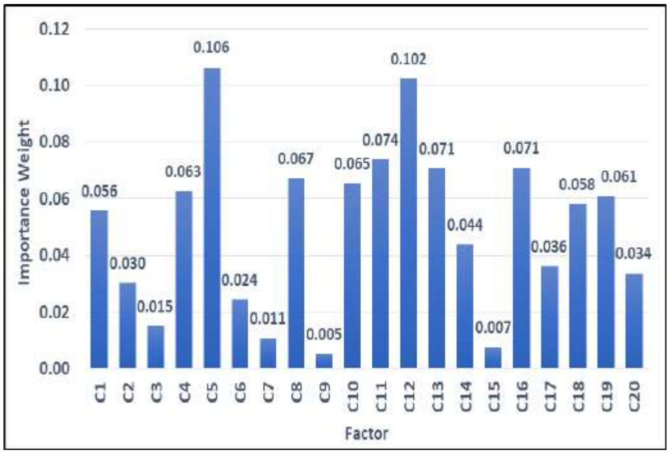

Figure 5. *Importance weights of factors*

It is seen that the values where D-R values are above zero affect other factors more. These are C16 [incorrect power transmission or frequency supply (50/60 Hz)], C4 [incorrect power supply (50 Hz instead of 60 Hz)], C6 (50 Hz pulley operating with 60 Hz power supply), C18 (bowl casing drain obstructed), C7 (high position of paring disc incorrect), C1 (friction elements worn or oily) and C15 (oil level in oil case is too low). As seen in the examination, it is very important to provide the voltage and frequency of the electricity to be given to the electric motor that will operate the separator correctly. Failure to supply electricity or incorrect supply will cause the separator not to work at all or to work incorrectly. After the correct electricity is supplied to the electric motor, it is important for the electric motor to transfer its rotational energy to the separator with the correct pulley in order to ensure the correct speed of the separator and separation. After the separator is running, if the outlet part of the separator is clogged, the separation will not be healthy since the separator will not be able to clean itself and the control unit will be warned via the outlet pressure of the separator, causing the separator to stop itself. If the high position of paring disc is incorrect, the separator will not be able to create outlet pressure while it is running and will release used oil/fuel, solid waste and water to the outlet, and will send a signal to the control unit to stop itself. If the friction elements are worn or oily, the friction elements will not be able to fully adhere to the pulley during the rotation of the electric motor and will not be able to fully transfer the speed which is needed to achieve proper revolution. For this reason, the separator will not be able to provide the speed required for separation and will release used oil/fuel to the solid waste and water outlet. If the oil level in the oil case is very low, there will be no problem in the separator operation at first, but later, since there will be insufficient lubrication and cooling in the lower bearing, the bearing will deteriorate very quickly. This will create vibration in the operation of the separator, causing the upper bearing to deteriorate via the shaft and finally the shaft to deteriorate.

Finally, the importance weights of the factors resulting from the calculations in step 7 are presented in Figure 5. In this case, those with the highest importance are C1, C5, C8, C10, C11, C12, C13, C18, and C19. The wear or lubrication of friction elements, deformation or wear of bearings, bowl imbalance, wear of vibration dampers in frame feet, bowl shaft bending, overheating, deformation or wear of upper and/or lower bearings, defect of the upper shaft bearing rubber damper, bowl casing drain obstructed, and upper bearing leakage were found to be of the highest importance. Here, the important factor is the experience gained by the experts owing to the failure they encountered, which is the reason for the different results between the importance weights. C20, C19, C13, C12, C10, and C5 were also affected by the other criteria. These are condensation, upper bearing leakage, defects of the shaft upper bearing rubber damper, overheating, deformation or wear of the upper and/or lower bearings, wear of the vibration dampers in the frame feet, and deformation or wear of the bearings. Separators are very sensitive equipment that consecutive parts inside affect each other. As can be seen here, while bearings can cause other failures, they are also the parts most quickly affected by incorrect assembly and imbalance in the bowl.

4. Conclusion

It is difficult to state a clear root cause for machines consisting of many interconnected parts, such as separators. Because the parts that make up the separator are interconnected and damage to any one of these parts will cause damage to the others. Separators are equipment that enable the ship to sail smoothly, ensure long-term operation of the machines like main engine and auxiliary generator, increase their performance, prevent the wear of materials such as fuel pumps and injectors, where fuel is actively used in the main engine and auxiliary generator, and make profits in the long term. Therefore, it should not be considered as fuel. The active operation of oil separators protects the moving parts of the machines and prevents damage to its crankshaft.

The C8 separator encompasses various parameters that can influence its operational efficiency, including bowl imbalance, contamination, and assembly inaccuracies. To ensure optimal performance, it is essential to adhere to the maintenance schedules specified by the manufacturer for the separators. Drawing on expert experience, several critical maintenance practices should be emphasized: regular replacement of bearings, thorough cleaning of the bowl, precise assembly with appropriate measurements, and conducting inspections at intervals established by the manufacturer. A significant concern in the operation of separators is the heightened risk of equipment failures resulting from assembly errors. Given the intricate design of separators, where numerous components are interrelated and rotate at high speed, even minor discrepancies in assembly or balance can lead to inadequate cleaning performance. Such deficiencies not only compromise the efficacy of the equipment but may also accelerate wear and deformation of the components. When the importance weight is examined, it can be seen that the factors C5 (bearing deformation or wear) and C12 (overheating, deformation or wear of the upper and/or lower bearings) are of high importance. According to the experience of experts, two factors of this importance are stated that it is known that C5 and others, which have the highest value and importance, will actually cause failures that will affect each other if the maintenance is not performed according to the manufacturer's recommendation, within the maintenance hours, with original spare parts and by authorized crew.

The factors that affect the other criteria are C16 [incorrect power transfer or frequency supply (50/60 Hz)] and C4 [incorrect energy supply (instead of 50 Hz, 60 Hz)], which will cause the equipment to not work properly, so there will be no efficiency from the separator and the equipment will be damaged. C16 and others, which have the most effect on other factors, cause the electric motor of the separator to fail to operate at all or to operate inadequately due to the lack of appropriate electricity or frequency to the electric motor that will enable the separator to operate. In addition, it is seen that the correct electrical voltage and frequency to the electric motor, the suitability of the friction elements in the electric motor and finally the harmony of the transmission element connecting the electric motor to the shaft of the separator have a high effect on the efficient operation of the separator. The factor most affected by the other criteria is C10, that is, vibration dampers in frame feet worn out. It is stated that the separator is the most affected factor as the balancing force acts on the vibration dampers in the frame feet to constantly balance even the smallest vibration during the initial start-up, stopping, and rocking of the ship in the wavy sea.

Generally, the situation seen by the experts in the application field is expressed as follows. The maintenance manual is not read sufficiently and due to this, the separator is maintained after more running hours, the spare parts are not used originally, the separator is repaired with the wrong spare parts due to the wrong material demand, the separation process is not effective or cannot be separated at all due to the installation of O-rings in the wrong place during maintenance. It is very difficult to diagnose failure due to inadequate cleaning of the maintained parts. In the future, separators produced for ships can be mounted with magnetic frame legs without being fixed to the ship. In addition, oil and fuel separators to be used on ships can be produced by creating an electromagnetic field or using a geared electric motor of an appropriate diameter instead of the bearings used in the separators. By this way, the most important causes of failure, determined according to expert opinions, are prevented. Subsequent research will focus on developing comprehensive maintenance manuals integrating expert insights and technological advancements to minimize separator failures.

Footnotes

Authorship Contributions

Concept design: S. Ayvaz, and A. S. Karakurt, Data Collection or Processing: S. Ayvaz, and A. S. Karakurt, Analysis or Interpretation: S. Ayvaz, Literature Review: S. Ayvaz, and A. S. Karakurt, Writing, Reviewing and Editing: A. S. Karakurt.

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Exploring the Role of Mission and Vision Statements in Maritime Transport: A Focus on Liner Shipping Companies

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Abstract

This study examines the strategic management of mission and vision statements of the top 100 liner shipping companies. By analyzing the content and components of these statements, this study assesses their effectiveness in guiding organizational behavior and aligning stakeholder expectations. Content analysis reveals that while self-concept and philosophy are emphasized, critical aspects like customer orientation and employee concerns are underrepresented. Vision statements prioritize clarity and stability but often lack the motivation required to motivate stakeholders. The findings suggest the need for a more balanced approach when crafting statements. This study offers recommendations for improving strategic communication practices in maritime companies, highlighting the importance of stakeholder involvement, regular updates and integration into daily operations. Enhanced mission and vision statements can significantly improve organizational alignment and performance.

Keywords: Mission statements, Vision statements, Liner shipping companies

1. Introduction

The maritime industry is a critical contributor to international trade and transportation. This involves various activities such as shipping, port operations, offshore energy, and marine tourism. Organizations strive to gain a competitive edge and meet their strategic goals in the maritime industry. In this rapidly evolving environment, maritime businesses must have a clear sense of purpose and direction to navigate the challenges that arise and seize opportunities. As businesses in this industry strive for long-term growth and a competitive advantage, developing clear mission and vision statements has become increasingly important. A crucial aspect of this process is the development and implementation of mission and vision statements [1,2]. These statements are guiding principles that shape an organization's direction, inform its decision-making, and inspire its stakeholders [2]. The mission and vision statements of an organization are essential strategic tools that communicate the organization's core values, beliefs, and long-term goals [3].

Mission and vision statements are vital for strategic planning, decision-making, resource allocation, and overall direction within an organization [4]. By outlining the organization's goals, principles, and mission, mission statements help stakeholders understand who they are and where they fit in. The importance of mission and vision statements has been widely recognized, and many organizations invest significant time and resources into crafting and communicating these statements [5].

Mission statements set the values and guidelines for how an organization operates and engages with stakeholders, whereas vision statements focus on future goals and motivate stakeholders [6,7]. Studies have demonstrated that mission statements give organizations a sense of purpose, guide resource allocation, and turn goals into actionable plans [8]. Studies have revealed that mission statements outline the primary goals of an organization, the essential reason for its existence, and the distinctive value it hopes to offer to its stakeholders or clients [9]. Additionally, mission statements set forth an organization's values, giving workers a sense of purpose and direction while also directing their decision-making. These statements help to align the organization's activities and resources toward a common goal [1,10].

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On the other hand, vision statement explain what an organization intends to achieve in the future. Vision statements set forth the organization's long-term goals and desired state. These statements articulate long-term goals and guide future practices, assisting organizations in preparing for change and maintaining focus [11,12].

Mission and vision statements are essential for organizational identity and unity. They unite members, provide shared meaning systems, and direct organizational actions [13]. These statements also contribute to organizational performance by motivating employees, shaping behaviors, and fostering commitment [14]. According to Taouab and Issor [15], organizational performance measures how well a company uses its resources to create value and consequently profits, while meeting the varied needs of different stakeholder groups. Bresciani et al. [16] asserted that internal and external influences impact the effectiveness of an organization. When employees understand and internalize the organization's mission and vision, they are more likely to be motivated, focused, and aligned with its strategic objectives. Studies have shown that organizations with clearly communicated and collectively shared mission and vision statements perform better than those without [1,10]. In addition, effective mission statements have been associated with improved firm performance, highlighting the significance of well-crafted statements in strategic planning [17].

Overall, the literature shows that mission and vision statements are critical in guiding organizational behavior and performance. However, their effectiveness is contingent on factors such as stakeholder involvement, communication of brand personality attributes, and the company's adaptability to industry norms. Further research is needed to explore the role of mission and vision statements in specific maritime subsectors and to identify best practices for their development and implementation.

From a regulatory perspective, public policy and international shipping norms have historically shaped the competitive setting in liner shipping, influencing tariff structures, market entry, and strategic alliances [18]. Recently, environmental regulations-such as stricter sulfur emissions limits-have introduced further complexity, driving investment in alternative fuels, innovative propulsion systems, and more efficient voyage planning [19]. Consequently, the liner shipping sector exemplifies a constantly evolving ecosystem that reflects, ongoing technological changes, trade patterns and, legal requirements.

2. Role of Mission Statements and Vision Statements in Liner Shipping

Liner shipping, which primarily involves scheduled maritime transport for containerized cargo, plays a significant role in global trade and supply chains. It is characterized by regularity, fixed services and the use of standardized container vessels [19]. This sector faces distinct operational and strategic dynamics compared to other maritime transport segments, such as bulk shipping or tanker operations, largely due to its high level of schedule reliability, port network integration, and strategic alliances among carriers [20]. Similarly, capacity management and vessel-sharing agreements have become common practices in liner shipping, allowing carriers to consolidate shipments, share resources, and reduce operating costs in highly competitive markets [21]. Port selection and terminal operations are critical for liner carriers' strategies, shaping global freight corridors and influencing regional economic development [20]. Regulations and international shipping policies also shape the liner shipping landscape, impacting pricing, service patterns, and entry barriers [18]. Overall, the liner shipping sector illustrates the interplay between technological advancement, global trade dynamics and, evolving regulatory pressures, making it a continuously adapting and strategically complex segment of maritime transport.

In the liner shipping sector, clear mission and vision statements serve as strategic cornerstones guiding organizational decision-making, stakeholder engagement, and long-term direction. In the liner shipping sector, mission statements are pivotal because they guide strategic decision-making, foster organizational unity, and communicate a carrier's core purpose to stakeholders. Furthermore, having a strong mission helps differentiate individual carriers and strengthens partnerships by signaling dedication to service quality, environmental responsibility, and consistent performance qualities that are increasingly valued in global maritime trade [18,21].

Recently, a growing body of research has the significance of mission and vision statements in several sectors, including the marine industry. A systematic review by Alegre et al. [22] compiled studies on mission statements, emphasizing the role that these statements play in establishing organizational culture and directing behavior. Bart [23] emphasized the complexity of mission statements, suggesting that they may consist of up to 25-component parts. Alolayan et al. [24] focused on key components of mission statements, including consumers, products, and services; market; technology; survival and growth commitment; philosophy; public image; employees; and distinctive competencies. Researchers have also investigated the impact of mission statement components on organizational performance [25]. The review of the literature in this area has revealed a lack of consensus on the components that a mission statement should contain. Abdalkrim [26] identified the mission statement as a key component of strategic planning activities, along with implementation, internal and external analysis, and control and evaluation. Desmidt et al. [27] conducted a 20-year meta-analysis on mission statements, highlighting their critical role in organizational success. Research has explored the link between mission statements and organizational performance, with studies such as Duygulu et al. [28] examining this relationship in small and medium-sized organizations. Additionally, research indicates that an effective mission statement can benefit an organization in several ways, including fostering a sense of purpose, offering guidance, acting as a focal point, guaranteeing unity of purpose, and directing goals and tactics. Yadav and Sehgal [29] explored how high-performing organizations define their mission, emphasizing the importance of a clear and compelling goal in mission statements. The advantages of including corporate ethos, brand personality attributes, and mission statement components in mission and vision statements were covered by Fitzsimmons et al. [30]. Babnik et al. [3] highlighted the significance of products and services as important components of mission statements. Penco et al. [31] emphasized the critical role of mission statements in firms' sustainability and growth, positioning them as tools for the strategic management process. The analysis of mission statement components in various contexts, such as hospitals, social enterprises, and educational institutions, has provided valuable insights into the diverse applications and impacts of these strategic documents.

An analysis of the similarities and distinctions among sectors and businesses in Switzerland has demonstrated the significance of online brand personality characteristics in establishing a distinct company identity using mission and vision statements. The effectiveness of mission statements on corporate reputation was also highlighted as an important consideration for competitiveness in the global market [32]. A key theme emerging from the literature is the potential impact of these statements on corporate identity and reputation. Research suggests that mission statements can effectively communicate a company's underlying core character or brand personality, influencing stakeholder perceptions [32]. Organizations can distinguish themselves from competitors and build a favorable market position by highlighting distinctive traits and values. Research has shown that mission statements can communicate and strengthen the intended organizational culture [3,33]. The content and emphasis of these statements can shape employee behavior, values, and commitment to the organization's goals. Clear and measurable objectives offer direction and clarity, potentially boosting overall performance. The importance and usefulness of mission and vision statements is increased when stakeholders are involved in their creation [3].

3. Crafting Effective Mission and Vision Statements

The process of developing and communicating mission and vision statements is critical to their effectiveness. Crafting mission and vision statements for maritime businesses is a critical step in defining their purpose, values, and future aspirations. Drawing from the extensive literature on mission and vision statements in various sectors, it is evident that these statements play a pivotal role in guiding organizational strategies, communicating values, and inspiring stakeholders [34-36].

An effective mission statement should be concise, memorable, and encompass the organization's core purpose, values, and unique competencies [10,37]. An effective mission statement should clearly articulate the organization's core values, objectives, products and services, philosophy, and priorities. It is a unifying theme that motivates and focuses employees, guiding them in their daily activities and strategic initiatives [12,38]. A well-formulated mission statement serves the purpose of not only conveying the purpose of an organization's existence but also delineating its course, priorities, and values, thus setting it apart from its rivals [30,39].

A compelling vision statement should describe the organization's aspirations, inspire stakeholders, and guide strategic choices. Vision statements should be future-oriented and aspirational and should provide a clear direction for the organization to strive toward [40,41]. They are crucial in aligning efforts, motivating employees, and signaling the organization's long-term goals to external stakeholders [42]. Involving stakeholders in the process helps organizations create statements that connect with employees, customers, and the community, fostering a sense of purpose and direction [6,43].

Mission and vision statements should not exist in isolation but should be integrated into the organization's overall strategic planning and communication efforts. To ensure they continue to be significant, impactful, and in line with an organization's strategic priorities, they should be evaluated, updated, and shared regularly [11,38]. One way to reinforce these is by incorporating them into daily operations and decision-making processes.

For maritime businesses, a well-crafted mission statement should summarize the fundamental values, goals, and operational focus unique to the maritime sector. The document should outline the organization's commitment to maritime safety, environmental sustainability, efficient operations and, customer service excellence. By clearly articulating these aspects, a mission statement can serve as a compass for decision-making and resource allocation within maritime businesses [30,44]. In parallel, the vision statement for a maritime business should project a forward-looking perspective that envisions the company's future position in the maritime sector. This should encompass goals related to innovation in maritime technology, expansion into new markets, sustainability initiatives, and leadership in maritime best practices. A compelling vision statement can inspire employees, attract much-needed workforce investors, and differentiate a business in a competitive industry [41,45]. Research suggests that mission and vision statements are not mere symbolic declarations but strategic tools that can significantly impact organizational performance. In the maritime business context, these statements can foster a culture of safety and excellence and position an organization for long-term success in the maritime industry [5,46].

3.1. Components of Mission and Vision Statements

The components of a mission statement have been extensively studied in the literature. Pearce and David [47] classified key components into, eight categories [22]. These components include target customers and markets, principal products and services, geographic domain, core technologies, commitment to survival, growth, profitability, key elements of company philosophy, self-concept, and desired public image. There are four essential components to mission statements: purpose, strategy, behavior, and company values [48]. These components focus on defining the fundamental reason for the organization's existence, outlining the strategic approach to achieving its goals, specifying the expected behavior and actions of the organization, and highlighting the core values that guide decision-making and operations. Mission statements commonly address questions about the organization's strategy and focus, such as "who we are" and "what businesses we are in" [49]. In addition, mission statements can outline target demographics, markets, geographical areas, fundamental technologies, and organizational philosophies to offer a full summary of the organization's identity and strategic objectives [28].

Vision statements within an organization provide several benefits, including ensuring that the organization's interests are embraced by all employees, facilitating activities, allowing for comparisons between activities, and focusing on the effectiveness of organizational change and transformation. It is emphasized that vision statements should be concise, embodying components such as conciseness, clarity, future orientation, stability, challenge, abstraction, desirability, and the ability to inspire as a whole [50-52].

4. Methodology

This research aims to systematically analyze the mission and vision statements published by liner shipping companies on their corporate websites in the context of the strategic management process. In this context, the websites of the top 100 liner shipping companies, as listed by Alphaliner, were analyzed, and the companies that included mission and vision statements were assessed based on the academic literature's effective mission and vision components.

According to the nine elements of a comprehensive mission statement identified by Pearce and David [47], content analysis was performed on the mission statements of liner shipping companies with mission and vision statements on their corporate websites. Furthermore, content analysis was conducted to assess the seven elements of a comprehensive vision statement identified by Kantabutra [50]. The MAXQDA 2024 program was used to code the mission and vision statements of the businesses as part of their content analysis. The vision and mission statements were coded using the hierarchical code and sub-code model of MAXMaps, a visual tool developed by MAXQDA 2024.

The Alphaliner company's top 100 companies, released on May 4, 2024, served as the sample. Considering the fleets of nearly all container operators globally, the Alphaliner top 100 offers a continuously updated rating of the 100 biggest container/liner operators and global capacity numbers. After analyzing the corporate websites of 100 companies, 47 of them had mission and/or vision statements. Thirty-five vision statements and 37 missions were looked at in the study. Table 1 lists the companies that comprise the research sample.

5. Findings

Fourty-seven organizations with mission and vision statements on their corporate websites were examined individually as part of the content analysis of the mission and vision statements of the liner shipping companies. The elements that each mission and vision statement contained were identified.

The results pertaining to the mission statements of the 37 companies in the sample are presented in Figure 1 and Table 2. Table 2 shows that no company has all nine mission components active simultaneously. Four businesses utilized 78% of the components in their mission statement, four businesses used 67%, eleven businesses used 56%, nine businesses used 45%, four businesses used 33%, and five businesses used 22% of the components in their mission statement, according to the research. The company has made a decision. Based on this research, it appears that company mission statements typically consist of five or four elements.

The organization's internal rules and procedures, designed to direct management and staff, are based on mission statements. Furthermore, upon examination of the nine components, it is noted that the "self-concept" component, included in

Table 1. *List of sampled companies*

Code	Company	Vision	Mission
S1	Mediterranean Shipping Company	✓	
S2	Maersk	✓	
S3	CMA CGM Group		✓
S4	Hapag-Lloyd		✓
S5	Evergreen Line		✓
S6	Yang Ming Marine Transport Corporation	✓	
S7	PIL (Pacific Int. Line)		✓
S8	KMTC	✓	
S9	X-Press Feeders		✓
S10	Zhonggu Logistics Corp.		✓
S11	UniFeeder	✓	✓
S12	Sea Lead Shipping	✓	✓
S13	Sinokor	✓	
S14	TS Lines		✓
S15	Regional Container L. (RCL)	✓	✓
S16	SM Line Corp.	✓	✓
S17	Emirates Shipping Line, the shipping company		✓
S18	Matson	✓	✓
S19	Ningbo Ocean Shg Co	✓	
S20	Arkas Line (EMES)	✓	
S21	Grimaldi (Napoli)		✓
S22	Sino Trans	✓	✓
S23	China United Lines (CULines)	✓	✓
S24	FESCO	✓	✓
S25	Samudera	✓	✓
S26	Tanto Intim Line	✓	✓
S27	Seaboard Marine		✓
S28	Namsung Shipping	✓	✓
S29	ASYAD Line, L.L.C.	✓	✓
S30	Temas Line	✓	✓
S31	Akkon Lines	✓	✓
S32	Turkon Line	✓	✓
S33	Transworld Group, Singapore	✓	✓
S34	Crowley Liner Services		✓
S35	Qatar Navigation (Milaha)	✓	✓
S36	MTT Shipping	✓	
S37	Boluda Lines	✓	✓
S38	HR Lines	✓	
S39	Eimskip	✓	✓
S40	Samskip	✓	✓
S41	Pan-continental Shg		✓
S42	Shipping Corp. of India	✓	✓
S43	Philippine Span Asia Carrier Corp.	✓	✓
S44	Medkon Lines	✓	✓
S45	Rifline	✓	
S46	VASI Shipping	✓	✓
S47	Shin Yang Shipping Sdn Bhd	✓	✓

33 mission statements (89%), is the most prevalent. The "philosophy" component, present in 29 mission statements (79%), appears to be the other significant component. This component is followed by the following: "product/services" (73%), "sustainability, growth, profitability goals" (49%), "customer" (43%), "public image" (41%), "market" (33%), and finally, "responsibility toward employees" (19%).

The following are examples of each mission statement component:

Customers: "Who are the customers of the company?"

- "……..................................all our business partners and stakeholders." (VASI Shipping, S46).
- "To customize Solutions for all Ship Owners……….." (Shin Yang Shipping Sdn Bhd, S47).
- "…………………..... to support our customers' feedering needs." (X-Press Feeders Group, S9).
- "…………….. with satisfied customers, …................." [Regional Container L. (RCL), S15].
- "…………………… to serve our customer best, ………………………" (SM Line Corp, S16).
- "……….provides customers with world class services, ..…." (Emirates Shipping Line, S17).
- "…… growing together with our customers for a better future…….." (Tanto Intim Line, S26).
- "…………… by offering customized solutions to our customers ….." (Akkon Lines, S31).

Upon examination of the aforementioned mission statements, it becomes evident that the term "customer" encompasses a broad spectrum of parties associated with maritime transportation, and 43% of organizations incorporate these expressions in their missions. The customer-focused approach maximizes customer pleasure while allowing target consumer groups to form close relationships with the company [53].

Products and services: "Which are the main offerings of the company?"

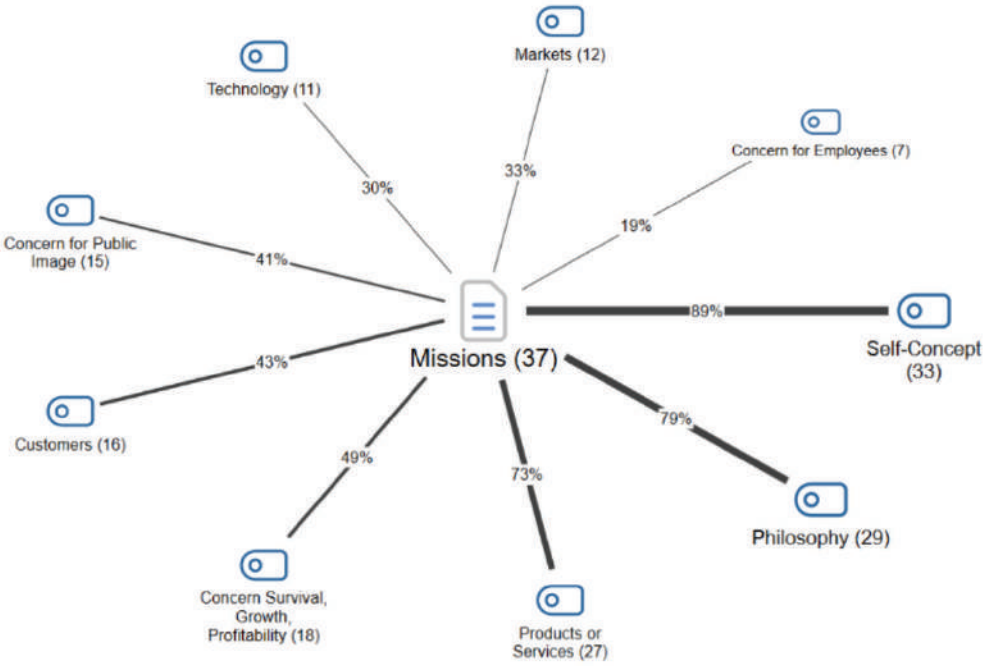

Figure 1. *Numbers and percentages of mission statement components*

Table 2. *Numbers and percentages of mission statement components*

Mission statements	Total	%
Customers	16	43
Products and services	27	73
Markets	12	33
Technology	11	30
Survival, growth, and profitability	18	49
Philosophy	29	79
Self-concept	33	89
Concerns regarding public image	15	41
Concerns for employees	7	19

- “………. easy customer experience in interisland cargo logistics…………” (Philippine Span Asia Carrier Corp., S43).
- “……………… to accelerate our fleet renewal program, introducing ever more eco-friendly container ships.” (Evergreen Line, S5).
- “……………………… reliable shipping and related services.”[PIL, (Pacific Int. Line), S7].
- “……………… high-quality services for the sea transport of passengers and freight, ” [Grimaldi (Napoli), S21].
- “……………… providing transportation services ……………………..” (Samudera, S25).
- “Respond and attend to the needs of the maritime transport and the harbor logistics ………” (Boluda Lines, S37).

Upon closer inspection of the aforementioned instances, it becomes evident that companies explain in their mission statements the industry to which they cater and the services they offer. Seventy-three percent of companies include these statements in their mission statements. Businesses can set themselves apart from their rivals by providing various services. The development, application, and assessment of business plans heavily rely on services [54].

Markets: “Where does the company compete?”

- “To create the most successful regional Multi-modal container logistics system ..” (Samskip, S40).
- “To create the best logistics solutions in Russia and Eurasia……………………..” (Fesco, S24).
- “…..… to be a leader in ocean transportation and logistics ………” (Seaboard Marine, S27).
- “To propel the development of Oman as a global logistics hub…… (ASYAD Line L.L.C., S29).

When the mission statements above are examined, it is noteworthy that the name of a country or the sector in which it operates is explained in the market/location dimension. Companies include these statements in their missions at a rate of 33%. In mission statements, companies should disclose to the public the markets they serve or, in other words, the facts about their target market [54].

Technology: “Does the organization prioritize technology?”

- "……..… in providing Comprehensive, Innovative and efficient Quality services………..." (Shin Yang Shipping Sdn Bhd, S47).
- "……………..based on internet big data,…………………..." (Zhonggu Logistics Corp, S10).
- "To innovate and improve as a trade facilitator……………….……..." (Sea Lead Shipping, S12).
- "………………… to deliver efficient, reliable, innovative and high-quality services for the sea transport of passengers and freight,…………….." (Grimaldi (Napoli), S21).

"Technology" describes innovation, big data, and technological advances in the aforementioned cases. It is evident that companies place high value on keeping up with technical advancements that are unique to their industry, and this is reflected in their goals. Thirty percent of companies have been observed to include these statements in their missions. Businesses attach greater importance to researching technological changes and developing technology because of increased competition and rapid differences in customer demands [55]. Digitalization, which is essential for companies to achieve their goals, is a significant issue in the maritime industry in terms of its competitive advantages and regulatory compliance.

Concern survival, growth, profitability: "Is the organization receptive to environmental, social, and community issues?"

- "…………… by the most economical & timely means as a professional freight forwarder.............…" (Pan Continental Shg, S41).
- "………….., evolving reliable and cost-effective business models to exploit emerging opportunities………" (Shipping Corp. of India, S42).
- "………………. to build efficient e-commerce platforms ……………" (Evergreen Line, S5).
- "……………thereby contributing to the global economic development" (SM Line Corp, S16).

Sustainability, growth, and profitability targets are employed in mission statements to indicate growth, development, success, and profit, as seen in the examples above. Companies are found to include these statements in their missions 49% of the time. Businesses currently place a high value on profitability targets for growth to be sustainable because, the growth idea gives them a sustainable feature [56].

Philosophy: "What are the fundamental principles, ideals, goals, and philosophical priorities of the company?"

- "…… to be "The Global Common Carrier" of choice, …………" (X-Press Feeders Group, S9).
- "………………… to build on our leading market position and expand the market share in our existing territories, enlarge the contents of our products and grow into new geographies." (UniFeeder, S11).
- "To be a fully integrated shipping enterprise……………….." (Emirates Shipping Line, S17).

These examples demonstrate how the goals of maritime corporations are reflected in their ambition to supply integrated services, increase their market share, and cater to a vast population. These assertions are part of the missions of 79% of the companies. Businesses' values and beliefs regarding their interactions with all their stakeholders, including employees, clients, suppliers, and the government, should be reflected in their mission statements [57].

Self-concept: "What is the primary competitive advantage or area of unique competence for the organization?"

- "With its strong organization and cultural structure; ……………………" (Medkon Lines, S44).
- "To uphold our position as a leading freight and logistics service provider,…..." (VASI Shipping, S46).
- "…………, we are "connecting the world across oceans". ……………...……..." (Hapag Lloyd, S4).

In their mission statements, the companies listed on the above list have highlighted their fundamental competencies, which include strong organizational and cultural structures as well as leadership positions. Eighty-nine percent of the companies have these statements in their missions. Customers' perceptions of the quality of a product or service should be improved by adopting the core competency approach, which should also be implemented in a way that makes it difficult for rivals to copy [58].

Concerns regarding public image: "Does the organization respond to environmental, social, and community concerns?"

- "……………………………, achieving excellence in Quality, Occupational Health, Safety and Environmental Management Systems." (Shipping Corp. of India, S42).
- "……..…while respecting the integrity of all men and women and the planet." (CMA CGM Group, S3).
- "……………create more values to benefit the society." [China United Lines (CULines), S23].

By examining the examples given above, it can be seen that companies have included language about their quality, health, safety, social responsibility, and environmental duties in their mission statements, reflecting the desired public image dimension. It was observed that 41% of companies had these statements in their missions. The targeted public image dimension, one of the mission components, is the perception of the company's social, societal, and environmental sensitivities [59].

Concern for employees: "Do workers see themselves as an organization's most valuable asset?"

- "………………………………..which are proficient, professional and perfectly suited to all our business partners and stakeholders." (VASI Shipping, S46).
- "……..dedicated Employees and benefits for our Shareholders". [Regional Container L. (RCL), S15].
- "Actively participating in creating employment and, developing human capital, …….. (Samudera, S25).

The aforementioned examples illustrate the different ways in which organizations define their human resources, demonstrating how important the aspect of employee accountability is in their mission statements. Companies incorporate these statements into their missions at a 19% rate.

Successful businesses share a clear vision, purpose, and goal and the flexibility to modify tactics in response to shifting internal and external environmental conditions. Examining the achievements of people, cultures, nations, and organizations reveal that they all have a vision [60]. The vision statements of the 35 companies in the sample are presented in Figure 2 and Table 3. Table 3 shows that three businesses are simultaneously operating with seven vision components. Twelve companies have six components in their vision statement, seven have five, nine have four, two have three, and one has two components and one component, according to the researcher's findings. The liner shipping companies in the sample consist of 6 and 4 parts, respectively. Additionally, when businesses were analyzed using the seven vision statement components, it was discovered that the "clarity" and "stability" components were the most frequently used (86%) components. The vision must be clear and straightforward enough to remain relevant even in the face of technological or market changes if it is to be embraced by all stakeholders and has their support for its overarching goals [61]. According to research, 86% of businesses have vision statements that follow the dimension of clarity. Surprisingly, 86% of businesses prioritize stability in their vision statements.

The words "abstractness" (80%), "future-oriented" (66%), "conciseness" (63%), "challenge" (57%), and "the ability to be desired and inspire" (49%) were highlighted in the vision statements.

The vision should offer a long-term, wide-ranging direction that maintains its value throughout time rather than being

Table 3. *Numbers and percentages of vision statement components*

Vision statements	Total	%
Conciseness	22	63
Clarity	31	86
Future orientation	24	66
Stability	31	86
Challenge	20	57
Abstractness	28	80
Desirability or ability to inspire	17	49

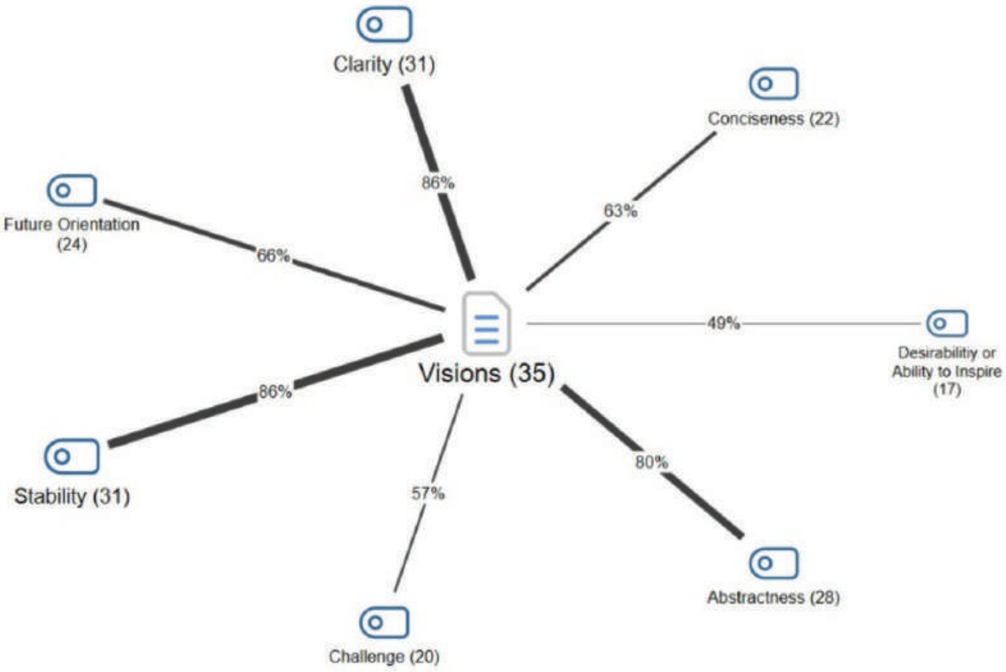

Figure 2. *Numbers and percentages of vision statement components*

a specific, one-time goal [61]. It was observed that vision statements that address an abstract subject are present in 80% of businesses.

The vision should focus on the long-term direction of the organization, offering guidance in response to future challenges and opportunities in its environment [61]. It is observed that vision statements with a future theme are present in 66% of the businesses.

A vision should be brief and to the point; however, this brevity must not hinder the clear communication of the organization's goals and objectives [61]. Vision statements suitable for conciseness were used by 63% of the sampled organizations. A vision statement should be between 11 and 22 words long to be effective and succinct [54]. Twenty two vision statements were between two and twenty-four words long.

A well-crafted vision should inspire individuals to strive toward challenging yet achievable goals and encourage them to give their best effort [61]. It is observed that 57% of companies have vision statements with a challenge theme.

The vision should represent an ideal that inspires followers and is worth pursuing. If it fails to resonate with followers, then securing their commitment will be difficult [61]. Vision statements concerning being inspiring and desirable are present in 49% of businesses.

Compelling visions that have a big influence on employee and customer satisfaction the bottom line of any company-have the following characteristics: challenge, abstractness, clarity, conciseness, future orientation, stability, desirability, or the capacity to motivate [52]. All three sampled businesses cover every aspect of their vision statements. These are ASYAD Line L.L.C., HR Lines, and Shipping Corp. of India.

- "We aspire to be among the top ten global integrated logistics service providers." (ASYAD Line L.L.C., S29).
- "Our vision is to be a premier container vessel operator in the region, flying the Bangladesh flag." (HR Lines, S38).
- "To emerge as a team of inspired performers in the field of maritime logistics, Offshore, Port and Terminal Management, serving Indian and global trade." (Shipping Corp. of India, S42).

According to Kessler and Chakrabarti [62], organizations that lack a clear vision-that is, have unclear project concepts-promote mistrust and disagreement among team members over what should be produced, which can lead to lengthy readjustments and arguments.

6. Discussion

The content analysis of mission statements from the top 100 liner shipping companies revealed notable trends and gaps. None of the companies included all nine components identified by Pearce and David [47], reflecting the variability in how these companies articulate their missions. The most frequently included components were "self-concept" (89%) and "philosophy" (79%). These components help define an organization's core identity and values, aligning with Kopaneva and Sias [13], who emphasized that a clear self-concept and philosophy are fundamental for guiding decision-making and aligning organizational activities with strategic goals.

However, the analysis also revealed a significant drop in the inclusion of customer orientation (43%) and public image (41%), suggesting a potential gap in the engagement of external stakeholders. This is critical in the maritime industry, where customer relationships and public perception significantly impact business success [63]. The limited focus on customer orientation contrasts with the findings of Bartkus et al. [64], who highlighted that mission statements should clearly communicate an organization's commitment to its customers to foster loyalty and trust.

The low inclusion of the "concern for employees" component (19%) is particularly concerning. The maritime industry relies heavily on skilled labor, and neglecting employee concerns could impact employee engagement and retention, which are crucial for operational efficiency and safety [65]. This finding contrasts with Kenneth and Bart Baetz [8] study, which stressed the importance of incorporating employee well-being into mission statements to enhance motivation and performance.

Vision statements showed a high frequency of "clarity" (86%) and "stability" (86%), emphasizing the need for a clear and consistent strategic direction. These components are essential for long-term planning and help stakeholders understand the company's future trajectory [42]. However, the "desirability or ability to inspire" component was included in only 49% of the statements, suggesting that although companies are clear about their future goals, they may not effectively inspire their stakeholders. Inspirational vision statements motivate employees and other stakeholders to align their efforts with the company's long-term goals to enhance, overall organizational performance [52].

The high inclusion of "abstractness" (80%) aligns with Kirkpatrick [12], who noted that abstract vision statements help guide broad strategic initiatives and inspire innovation. However, [66] the lower emphasis on "challenge" (57%) suggests that companies may not be sufficiently emphasizing the ambitious aspects of their vision, which can drive innovation and continuous improvement [67].

The comparison of mission and vision statements reveals distinct strategic focuses. Mission statements primarily define the organization's current identity, values, and operational focus, providing a foundation for daily decision-making and resource allocation [66]. In contrast, vision statements articulate long-term aspirations and goals, providing a company with a future-oriented roadmap. This distinction is critical for aligning short-term actions with long-term strategic objectives.

The variability in the comprehensiveness of these statements among top-liner shipping companies indicates differences in strategic communication maturity. Companies with more comprehensive statements are likely better positioned to convey their strategic intentions clearly, align stakeholder expectations, and achieve better organizational outcomes [64,68]. However, the overall lack of focus on certain components, such as employee concerns and inspirational elements, suggests that even leading companies have room for improvement in their strategic communication practices.

The gaps identified in maritime mission and vision statements, particularly regarding customer orientation (43% inclusion) and employee concerns (19% inclusion), align with broader trends observed across other industries. For instance, Desmidt and Prinzie [69] found that although retail organizations often use mission statements to enhance customer orientation and organizational sensemaking, inconsistencies remain in fully addressing diverse stakeholder needs. Similarly, Bart and Tabone [70] highlighted that healthcare mission statements frequently emphasize employee well-being and organizational alignment, demonstrating a commitment that contrasts with the maritime sector's limited focus on employee concerns. Kemp and Dwyer [71], in their analysis of airline mission statements, noted a strong emphasis on customer-centric language, illustrating a potential avenue for maritime organizations to adopt customer-focused strategies and strengthen stakeholder relationships. Additionally, Sufi and Lyons [72] critique of mission statements in the hospitality sector underscores the necessity of balancing internal priorities, such as employee engagement, with external priorities like customer satisfaction. These comparisons suggest that the gaps identified in maritime mission and vision statements reflect broader trends in strategic communication across various sectors.

7. Results

The content analysis of mission and vision statements from the top 100 liner shipping companies provides insightful observations on strategic communication in the maritime industry. The findings underscore the importance of components such as self-concept, philosophy, clarity, and stability. However, the relatively low emphasis on customer orientation, employee concerns, and inspirational elements points to areas for potential enhancement.

To maximize the effectiveness of mission and vision statements, maritime companies should strive for a balanced inclusion of all critical components. This comprehensive approach ensures that these strategic documents not only define organizational identity and future aspirations but also address all stakeholders' needs and expectations. By doing so, companies can enhance stakeholder alignment, foster a unified organizational culture, and drive better performance outcomes.

Enhanced stakeholder involvement: This step actively involves employees, customers, and other stakeholders in developing mission and vision statements. This inclusion can ensure that the statements resonate with all parties and align with their expectations, fostering greater buy-in and commitment [73,74].

Regular updates and reviews: Periodically review and update mission and vision statements to reflect changing market conditions, technological advancements, and evolving stakeholder expectations. This practice ensures that the statements remain relevant and effectively guide strategic decision-making effectively [75]. However, data such as user-generated content are much more accessible [76] due to social networking platforms, which companies can use to adapt and update their strategies to respond to stakeholder wishes.

Integration into daily operations: This step embeds mission and vision statements into daily operations and decision-making processes. This integration can help ensure that organizational activities are consistently aligned with strategic goals, enhancing coherence and focus across the company [77].

Focus on inspirational elements: Enhance the inspirational aspects of vision statements to motivate and engage employees and other stakeholders. An inspiring vision can drive innovation, encourage commitment, and differentiate a company in a competitive industry [50,51]

Comprehensive Employee Orientation: Ensure that mission statements address employee concerns comprehensively. This focus can foster a supportive work environment, enhance employee satisfaction, and improve retention, all contributing to overall organizational success [8].

By adopting these recommendations, maritime companies can strengthen their strategic communication practices, align organizational efforts with strategic goals, and enhance their competitive position in the global maritime industry.

Only 47 of the top 100 organizations that were examined in the study had mission and vision statements available. This restriction limits the applicability of the findings to the whole marine industry. This could be addressed in future studies by examining mission and vision statements from more businesses and using a larger sample. Further research is required to explore the impact of mission and vision statements on specific organizational outcomes in the maritime industry. Investigating how these statements influence factors such as employee engagement, customer satisfaction, and financial performance can provide deeper insights into their effectiveness.

Additionally, examining best practices for crafting and communicating mission and vision statements across different maritime subsectors can help identify strategies for optimizing their impact.

8. Conclusion

In conclusion, mission and vision statements are not merely symbolic declarations but strategic tools that can significantly influence organizational behavior and performance. By addressing the identified gaps and leveraging the strengths highlighted in this analysis, maritime companies can enhance their strategic communication, foster stakeholder alignment, and achieve long-term success in the competitive maritime industry.

Footnotes

Authorship Contributions

Concept design: G. Tuğdemir Kök, and T. T. Türkistanlı, Data Collection or Processing: G. Tuğdemir Kök, Analysis or Interpretation: G. Tuğdemir Kök, and T. T. Türkistanlı, Literature Review: T. T. Türkistanlı, Writing, Reviewing and Editing: G. Tuğdemir Kök, and T. T. Türkistanlı.

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Advantages and Disadvantages of Using Electric Tugboats: A Systematic Review

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Abstract

The maritime industry is increasingly focusing on sustainability and reducing environmental impact, which has generated growing interest in adopting electric propulsion technologies for tugboats to reduce emissions in ports. This study analyses the advantages and disadvantages of electric tugboats through a systematic review conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysesmethodology, complemented by a focus group of industry representatives to validate the results. By synthesising information from forty-two carefully selected studies, the analysis highlights environmental benefits such as reduced greenhouse gas emissions, lower noise pollution, and decreased operational costs. However, the research also identifies significant challenges, such as high initial costs, limited range, and infrastructure requirements for port electrification. The focus group findings confirm these conclusions, providing practical insights into the operational feasibility and potential for large-scale adoption. The study underscores the need to align technological advances with policy incentives to facilitate the sustainable transition of the maritime industry.

Keywords: Electric tugboats, Sustainable maritime industry, Emission reduction, Green technology, Energy efficiency

1. Introduction

In recent years, electric propulsion for tugboats has gained popularity as the marine sector has placed a greater emphasis on sustainability and minimizing its adverse environmental effects. This change attempts to reduce emissions and encourage environmentally responsible port operations. Given the pressing need for more environmentally friendly options, the current study examines the benefits and drawbacks of electric tugboats, a crucial subject for the shift to greener marine transportation [1].

Around 80 per cent of global trade is conducted by sea. However, this business has a severe environmental cost due to its reliance on fossil fuels, noise pollution, and high greenhouse gas emissions. Despite making up a small fraction of the global fleet, tugboats are disproportionately liable for port pollution due to their frequent and intensive use in port operations. With over 21,000 units worldwide, the tugboat sector produces almost 40 million tonnes of CO_2 yearly, equivalent to the emissions of seven million cars. Although tugs only contribute 4% of all maritime pollutants, they have a substantial localised impact on air quality in coastal and port regions [2]. Notably, they are responsible for 14% of NO_2 emissions, 19% of CO_2 emissions, and 7.7% of SO_2 emissions in Europe annually, highlighting the need for immediate action to lessen their environmental impact [3].

Electric tugboats are becoming a viable substitute in light of tighter emission standards and the global shift to renewable energy. They have the potential to significantly lower port emissions while maintaining adherence to international environmental guidelines. Thus, this study aims to thoroughly examine electric tugboats, weighing the benefits and drawbacks of incorporating them into contemporary maritime operations, as well as assessing their environmental impact.

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2. Materials and Methods

2.1. Database and Search Strategy

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [4] standards to guarantee rigour and transparency in selecting and evaluating the scientific literature. The goal was to examine the benefits and drawbacks of electric tugboats as a potential green maritime transportation option.

The Web of Science, Scopus, ResearchGate, and Google Scholar were the primary databases used to find pertinent articles, focusing on English-language publications. Without regard to time constraints, the search covered studies published until November 7, 2024, guaranteeing that the most recent advancements in the discipline were included.

The researchers worked together to create a thorough search strategy, using the keywords “electric” and “tugboats”(see Table 1), to increase the relevance of the results that were returned.

2.2. Inclusion and Exclusion Criteria

Strict selection criteria were employed to guarantee a targeted analysis: only original, English-language papers from reputable scientific publications that specifically examine electric tugboats in a marine setting were included. Review articles, papers without full text, and research not focused explicitly on electric tugboats were disqualified to preserve relevance and prevent reliance on secondary sources.

2.3. Selection

Zotero was used to arrange the identified studies, thereby making reference and analysis easier. To guarantee unique references, duplicate articles were automatically eliminated. Full texts were checked as needed, and titles and abstracts were manually examined according to the inclusion criteria. The research team cooperated with the selection process, guaranteeing uniformity and relevance in the selected papers. Zotero was used to arrange the identified studies, thereby making reference and analysis easier. To ensure unique references, duplicate articles were automatically eliminated. Full texts were checked as needed, and titles and abstracts were manually examined following the inclusion criteria. The research team cooperated with the selection process, guaranteeing uniformity and relevance in the selected papers.

2.4. Results

A first search turned up 877 articles. One hundred and sixtyitems were left for examination after 113 duplicates were eliminated, and 539 articles were excluded using automated algorithms. After a full-text review, 81 articles were eliminated, and 65 more were eliminated based on a manual evaluation of the titles and abstracts. Sixty-eight items were left for consideration, after 11 of the 79 remaining articles were unavailable. Of these, 42 publications were selected for the final study after 7 were found to be incomplete and 19 were judged unrelated to electric tugboats. Two supplemental articles were added to bolster the PRISMA approach and the insights gathered from focus groups (see Figure 1).

3. Literature Review

3.1. The Role and Evolution of Tugboats

Compact and powerful, tugboats move big ships through narrow spaces like ports and waterways. They help with docking and undocking maneuvers, rescuing, moving heavy equipment like oil rigs, and putting out marine fires. In light of significant developments in propulsion technology, tugboats have evolved substantially over time, moving from human-powered systems to steam engines and then to contemporary diesel engines.

A significant turning point in tugboat history was reached in 1802, when the Charlotte Dundas, the first steam-powered tugboat, was built in Scotland. This vessel revolutionised the industry and paved the way for subsequent developments with its exceptional mobility and tractive force. Because of their advanced propulsion systems, modern tugboats can operate efficiently in both inland and open-water environments. They are also crucial in maritime disasters, including platform salvages, disaster relief, and assisting large ships in challenging conditions like high currents or winds [5,6].

3.2. The Environmental Impact of Tugboats and the Need for Greener Solutions

Although tugboats are essential to maritime activities, they have a substantial effect on the environment. The marine sector, adopting cutting-edge technology such as dual-fuel engines that can run on both conventional and greener fuels, and liquefied natural gas (LNG)-powered engines that emit

Table 1. *Search strings and results in four databases*

Database	Search string	Results
Web of Science	(((TS=(tugboats))) OR TS=(tugs)) AND TS=(electric)	118
SCOPUS	(TITLE-ABS-KEY (electric AND tugboat) OR TITLE-ABS-KEY (electric AND tugs))	407
Google Scholar	electric tugs OR electric tugboats	244
Research Gate	electric tugs OR electric tugboats	108

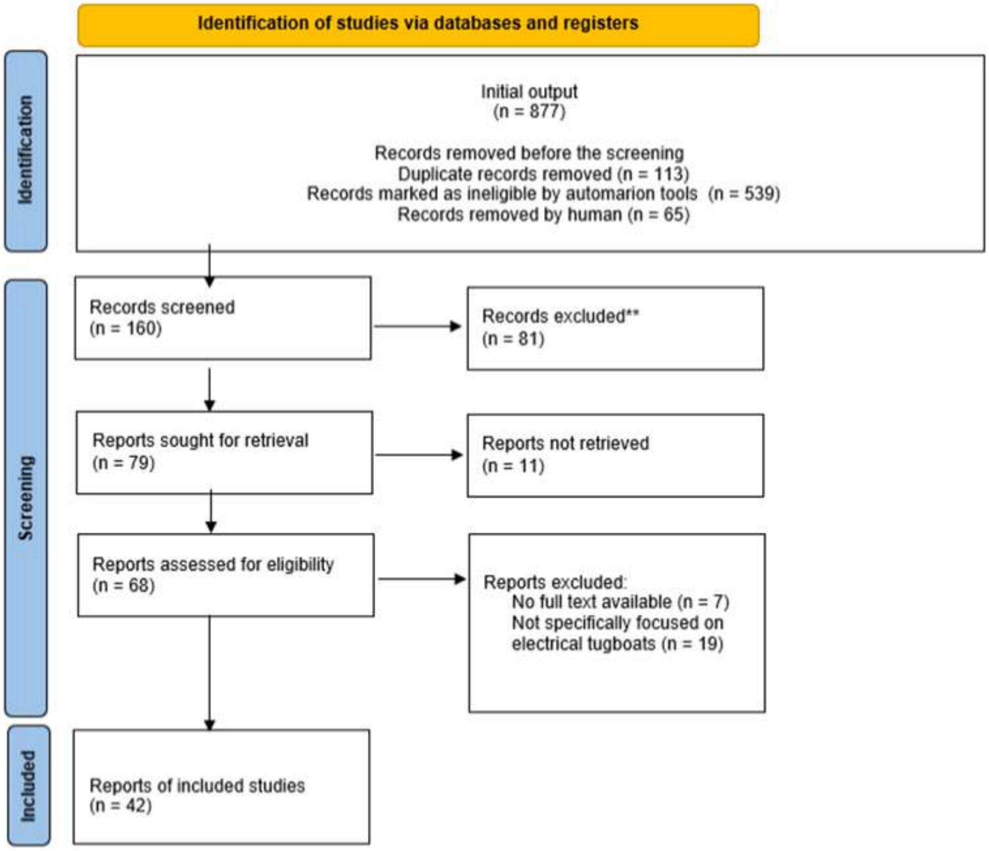

Figure 1. *Flow diagram of the included and excluded studies*

fewer pollutants, has acknowledged the pressing need to reduce emissions [7]. Combining electric and diesel power, hybrid propulsion systems provide a balanced method of increasing efficiency and lowering pollution. Additionally, alternative fuels like hydrogen and methanol are showing promise as long-term solutions. Additionally, by improving combustion, modern fuel injection technologies reduce pollution [6,8,9].

A baseline study conducted in the Gulf of İzmit, Türkiye, demonstrated the effect of tugboats on air pollution. Over three months in 2020, tugboats in this region generated 7,598.65 tons of pollutants, accounting for almost 10% of all ship emissions. This work laid a solid foundation for future research because it was the first to comprehensively analyse the pollution caused by port tugboats [3].

Tugboats contribute significantly to urban air pollution due to their high emissions of CO_2, NO_2, and SO_2. In ports, they are responsible for 14% of NO_2 emissions, a major contributor to urban smog. Adopting sustainable technology, creating emission control zones, and improving fuel quality are crucial in order to lessen these environmental effects. Furthermore, developing successful policies to limit port pollution depends on long-term monitoring of vessel traffic and emissions [10].

3.3. Research on Diesel-electric Systems for Tugboats

Numerous studies have explored ways to make tugboats' diesel-electric (DE) propulsion systems more sustainable and efficient. A mathematical model for DE systems utilising AC distribution was created by Guo et al. [11] (2005), who also examined aspects, including battery density, efficiency, and economic feasibility. A cost optimisation model for certified engines was presented by Solem et al. [12] (2015), who assessed NO_2 emissions, fuel consumption, and investment costs. Although a five-year payback period was impractical, their research revealed that profitability rose dramatically over time, offering a valuable tool for optimal diesel engine configurations [13].

In a different study, Kumar et al. [14] (2018) used MATLAB Simulink to compare diesel engines with fixed and variable speeds for an Indian tugboat. The results showed that fixed-speed engines performed better than conventional diesel systems, while variable-speed engines provided better fuel economy and reduced pollution. According to this study, DE systems can lower expenses, increase productivity, and lessen the systems' adverse environmental effects, making them an excellent option for contemporary tugboat design [15].

3.4. The Emergence of Electric and Hybrid Tugboats

Recent research on electric tugboats utilises cutting-edge technologies and energy management algorithms to maximise energy efficiency and lower carbon emissions. Predicting operational loads is a crucial research topic for effectively managing fuel and battery energy usage. Vu et al. [16] (2015) (suggested that energy management algorithms, based on known and unknown load profiles, consider factors such as energy consumption, battery state of charge, and energy losses. This method ensures effective resource allocation by dynamically adjusting the power distribution between generators and batteries through linear programming [16,17].

With techniques based on the Equivalent Consumption Minimization Strategy (ECMS) showing potential fuel savings of up to 10%, depending on load conditions, diesel-electric hybrid systems are also attracting more attention. While adaptive ECMS works better in low-load situations, constant ECMS is most effective under regular loads. Another viable way to cut emissions is to include LNG in hybrid or all-electric tugs. The Borgøy tugboat serves as the prime example of the invention, as it is the first LNG-powered vessel, which achieves remarkable energy economy and traction with a cryogenic tank and a 3,410 kW gas engine [8,18,19].

3.5. The Global Adoption of Electric Tugboats

Globally, the shift to electric and hybrid tugboats is accelerating. Ports like Rotterdam and Singapore have used electric tugs to cut emissions and boost productivity. Through integration with cutting-edge port technologies, this transformation has led to a decrease of almost 20% in overall emissions and by almost a shorter turnaround time in the Port of Rotterdam [20].

The debut of California's first all-electric tugboat, eWolf, in San Diego marks a critical turning point in the acceptance of electric tugboats. Diesel fuel is no longer necessary because the eWolf runs solely on electricity thanks to a 6.2 megawatt-hour battery. Its below-deck battery pack powers its propulsion system, which is refueled by, a shore-based power system that is part of an innovative microgrid with solar-powered energy storage containers [21].

Another noteworthy electric tugboat project is Sparky, the world's first full-size electric tugboat. built in Auckland, New Zealand. It is predicted to reduce CO_2 emissions by 465 tonnes a year. Its 2,240 battery energy storage system can perform up to four port manoeuvres on a single charge.

The ZEETUG45 tugboat in Istanbul, Turkey, is a remarkable example of a zero-emission, fully electric tugboat equipped with an azimuth stern drive system. With a draft of 4.32 metres and dimensions of 26.2 metres by 10.6 metres by 26.2 metres, the ZEETUG45 is specifically designed for port operations. It can achieve up to 12 knots and generate a pulling force of 49 tonnes. Its propulsion system is powered by a 2,215 kWh battery pack that can recharge from 25% to 90% in under 110 minutes.

Furthermore, three smaller electric tugs from the **ZeeTug30 series-Gisas Power, Gisas Power II, and Gisas Power III-**with a 30-ton bollard draw and a speed of about 10 knots are now in use. These tugboats run on Corvus energy storage systems, which can be fully recharged in less than an hour. These systems power two propulsion motors that are coupled to azimuth thrusters. Gisas Power alone has saved about 560.6 tonnes of CO_2 emissions and finished about 2,749 jobs since the start of its operation.

The Smart Tug Energy Management Technology-*STEMS* on the ZEETUG45 maximises electrical energy usage, prolongs battery life, and tracks real-time performance to improve efficiency. This technology gives operators useful information, thereby lowering running expenses and increasing operational efficiency.

Future electric tugboats are planned to be developed as larger ZeeTugs with up to 80 tons of bollard pull and incorporate hydrogen-battery hybrid technology (H2ydroTug60) to increase their operational capabilities and range [22].

3.6. The Future of Sustainable Tugboats

Technological developments in vessels, especially in creating sustainable tugboats, are strongly related to the trend toward greener ports and maritime activities. The need for more efficient and clean tugboats is growing as ports invest in alternative fuel infrastructure and enforce stricter environmental rules. Aggressive goals for cutting greenhouse gas emissions in the maritime industry are set by the European Union (EU) Climate Law and the Fit for 55 legislative package. Essential laws like the Alternative Fuels Infrastructure Regulation, the FuelEU Maritime Regulation, and the expansion of the EU Emission Trading System, are crucial in determining how tugboat propulsion develops in the future. By requiring alternative fuels, constructing port-side charging stations, and increasing energy efficiency, these regulations support the shift to environmentally friendly maritime transportation [23].

In this regard, cutting-edge initiatives like eWolf, ZEETUG45, and Sparky represent the transition to greener maritime technology. They are consistent with EU goals to have a climate-neutral shipping sector by 2050. Some factors, such as cost, regulatory compliance, and environmental impact, influence the selection of propulsion systems and fuel alternatives. These technologies are becoming increasingly feasible due to long-term savings and operational efficiencies, even with their high initial investment costs. The necessity of industry-wide collaboration to hasten the adoption of sustainable solutions is emphasized by collaborative programs such as FASTWATER and Horizon 2020 [24-26].

Another collaborative program is the Greenport Alliances project, which aims to advance sustainability and green capabilities in the maritime port services industry. It seeks to maximize the interaction between people and current technology to lower fuel consumption and improve sustainability in port operations.

Sustainable tugboats and electric port operations are becoming practical and necessary steps toward lowering maritime emissions and enhancing operational efficiency. Creative projects and regulatory frameworks have helped make these developments possible. These developments have opened the door for a more environmentally responsible future for the sector by setting a new global standard for effective, eco-friendly, and climate-neutral maritime transportation.

3.7. Advantages and Disadvantages of Electric Tugboats

Switching to electric tugboats is a significant step toward sustainable maritime operations, as it has financial and environmental advantages. The maritime sector is under growing pressure to lower emissions and increase energy efficiency; electric propulsion is starting to show promise as a substitute for conventional diesel-powered ships. But even with improvements in battery technology and government backing, issues such as high upfront costs, limited charging infrastructure, and operational limitations still exist. With an emphasis on the significant elements impacting their industry acceptance, Table 2 thoroughly assesses the benefits, drawbacks, opportunities, and difficulties related to electric tugboats.

Table 2. *Advantages, disadvantages, opportunities, and challenges of electric tugboats*

Source	Advantages	Disadvantages	Opportunities	Challenges
Gillingham and Huang [2] (2020)	Reduced CO_2 and NO_x emissions.	Higher initial cost	Growing regulatory pressure towards greener maritime solutions	Dependence on the energy grid and charging at ports.
Chen et al. [27] (2023)	Lower operational costs; Renewable energy integration.	Limited battery capacity; There are few charging ports.	Battery and energy management advancements; Renewable energy collaboration.	Uncertainty in battery technology lifespan and replacement costs; Challenges in standardising electric propulsion systems across global fleets.
Ortega-Piris et al. [28] (2022)	Less noise pollution; Better work conditions.	High port infrastructure costs.	Potential government incentives and funding for electrification projects.	Limited real-world operational data on electric tugboat performance.
Vu et al. [29] (2014)	Better fuel efficiency; Real-time power optimisation.	Energy storage degradation; Battery disposal concerns.	Increasing demand for low-emission tugboats in urban port areas.	Market resistance; Risk of supply chain disruptions affecting battery availability.
Kumar et al. [30] (2019)	Better manoeuvrability.	Battery safety risks.	Wireless charging solutions.	Limited skilled workforce for maintaining electric tugboats.
Mirza [31] (2024)	Lower maintenance costs.	Longer refuelling/ recharging times.	Hydrogen fuel cell integration.	High initial costs.
Chua et al. [32] (2018)	Fewer mechanical failures.	Electricity price dependency.	Public-private electrification projects.	Difficult diesel-to-electric retrofitting.
Devarapali et al. [22] (2024)	High energy efficiency (90% vs. 30-40% for diesel).	Expensive batteries, Limited range	Modular battery upgrades; Growing regulatory support for green shipping initiatives.	Training requirements; Uncertainty in economic viability.

***Table 2.** Continued*

Source	Advantages	Disadvantages	Opportunities	Challenges
Kozlowski and Leblowski [33] (2023)	Low maintenance; instant full-power operation; grid connectivity.	Insufficient charging infrastructure; Battery lifespan concerns.	Rapid-charging stations; Hybrid solutions: Expansion of zero-emission shipping corridors.	Slow adoption; Unpredictable battery tech; Costly port electrification.
Windover et al. [34] (2012); Raja Singh et al. [35] (2021)	High energy efficiency; Lower energy consumption; Reduced operating costs.	Grid dependence; Operational complexity.	Smart grid integration; Energy optimisation.	Dependence on renewable energy infrastructure.
Karacay and Ozzosysal [36] (2021)	Lower fuel costs; Reduced environmental impact.	High battery replacement cost.	Cheaper renewable energy and batteries.	High upfront transition cost.
Bernardinis and Moussodjii [37] (2019)	Lower emissions, noise.	High infrastructure investment.	Smart ports and energy balancing.	Ensuring compliance with evolving maritime emission regulations.
Dima et al. [38] (2022)	Renewable-powered charging; No direct emissions	Low battery energy density; Insufficient charging station energy replenishment.	Eco-friendly ports; Battery-fuel hybridisation.	Port upgrades; Charging reliability; Energy density limits.
Vrijdag et al. [39] (2019)	Long-term cost savings.	High cost of batteries and charging infrastructure power grids.	Financial incentives; Industry collaboration; Stronger environmental regulations.	Cost barriers for smaller ports; Slow charging network expansion.
Xin et al. [40] (2023)	Cleaner air in ports.	Battery capacity limits.	Higher-density; fast-charging batteries; Solar integration.	Costly battery replacements; Charging station logistics.
Karagkouni and Boile [41] (2024)	Port decarbonisation.	Expensive grid upgrades and charging stations.	Modernising port energy systems benefits overall port logistics and vessel coordination.	Grid overloading risks.
Li et al. [42] (2023)	Sustainability and lower fuel costs	Industry conservatism; High initial costs.	Training programs; Financial incentives.	Profitability concerns, Port upgrades. Industry resistance success stories.

3.8. Key Advantages of Electric Tugboats

With their substantial economic and environmental advantages, electric tugboats are radically changing the marine sector. Their significant decrease in CO_2 and NO_2 emissions is one of their main benefits, which makes them a more environmentally friendly option than tugboats that run on diesel [2]. In addition to lowering energy consumption and improving fuel economy, this switch to electric propulsion eventually lowers operational expenses [16,35].

According to Devarapali et al. [22] and other reliable sources [43,44], electric motors have a conversion efficiency of above 90% when using energy for productive activities. Diesel combustion engines, on the other hand, only use 30-40% of the energy produced by burning fuel, making them far less efficient.

Research conducted by the Port of San Diego found that, compared to their diesel-powered equivalents, electric tugboats significantly reduced energy usage per assisted vessel by almost 70% [22].

Electric motors can run quickly at full power because they don't need fuel to pre-heat, greatly improving mobility and operating response times [45]. Additionally, fewer moving parts mean fewer maintenance expenses because costly replacements and frequent repairs are avoided [31].

Integrating renewable energy sources like solar and wind power decreases reliance on fossil fuels, further improving financial sustainability.

In addition to their positive environmental effects, electric tugboats can power towed vessels, allowing them to switch off their diesel generators before port entry, lowering fuel consumption and pollution hazards. The advancement of smart port integration maximises efficiency and minimises wasteful energy use by enabling real-time monitoring via IoT, Big Data, and AI-driven energy management [37].

3.9.Main Disadvantages and Limitations of Electric Tugboats

Electric tugboats have numerous advantages, but some drawbacks prevent their widespread use. One of the biggest obstacles is the high initial investment cost, mainly caused by the costly lithium-ion battery technology and the infrastructure needed for port electrification [22,40]. Electric tugboats are less practical for long-distance towing or continuous operations in busy ports due to battery restrictions that limit their operational range [16,40].

Another issue with relying on charging infrastructure is that many ports do not have enough fast-charging stations, which causes operational disruptions [45]. Moreover, battery deterioration over time lowers efficiency and calls for costly replacements or backup battery systems, which raises long-term expenses further [40].

Despite electric propulsion's green reputation, another issue is the lack of clarity surrounding battery recycling and disposal, which raises questions about environmental sustainability. Furthermore, some ports rely on electrical networks that run on fossil fuels, reducing the total ecological advantages of electric tugboats [29].

Electric tugboats are less feasible for time-sensitive tasks due to operational delays caused by longer fueling/recharging times than those of diesel engines [31]. Integrating electric power management systems with maritime operations increases complexity and necessitates a significant investment in grid improvements and maintenance know-how [46,47].

4. Future Opportunities and Growth Potential for Electric Tugboats

Despite these disadvantages, the switch to electric tugboats offers many advantages. The increasing regulatory pressure on the marine sector to embrace green solutions encourages ports and businesses to invest in sustainable technologies [2]. Government initiatives, including financial incentives, carbon levies, and subsidies for renewable energy, can assist ports in switching to electric fleets while lowering their reliance on fossil fuels [40].

Improvements in energy management and battery storage technologies will boost productivity and lower operational expenses. By creating modular charging infrastructure and fast-charging stations, downtime can be reduced, and electric tugboats can continue to operate without significant interruptions [22].

Another exciting prospect is the combination of smart grids with electric tugboats, enabling AI-driven automation to enhance energy delivery. To further reduce operating expenses, ports can increase their renewable energy infrastructure by installing offshore wind turbines and solar panels to power tugboats [38].

In 2023, 24.5% of the EU's total energy consumption came from renewable sources, according to DNV [43] and Eurostat [48]. One of the most essential steps toward sustainable, carbon-neutral maritime transportation is the integration of renewable energy sources into electric tugboat operations. Ports and shipping firms can reduce their reliance on fossil fuels and emissions, and increase efficiency by using renewable energy and storage. In addition to port infrastructure, renewable energy sources can be integrated into electric tugboats. While hydrogen fuel cells and battery-electric propulsion increase range and versatility, solar panels can augment power. Regenerative braking is another technique certain boats use to recover energy while decelerating.

Using renewable energy in electric tugboat operations has several advantages. Lowering emissions and enhancing air quality produces a more sustainable maritime industry. Lower prices for renewable energy eventually result in even lower operating costs. Renewable energy sources give ports greater resilience and independence, reducing their susceptibility to price swings and grid outages.

Renewable integration is crucial since regulatory frameworks, such as those from the EU and the International Maritime Organization, increasingly support green maritime activities. Renewable energy sources and electric propulsion offer the sector a game-changing opportunity. Even though there are still obstacles to overcome, sustained investment in storage, clean energy infrastructure, and hybrid propulsion will hasten the switch to electric tugboats with zero emissions, guaranteeing sustainability and long-term financial savings.

By working together, governments and private enterprises can provide cost-sharing arrangements that lessen the financial strain on particular ports while accelerating investment in electric tugboat technology [40]. Concerns about battery constraints can be allayed by creating hybrid electric solutions that combine batteries with alternative fuels such as LNG to increase range capabilities [49].

4.1. Significant Challenges and Barriers to the Adoption of Electric Tugboats

Implementing electric tugboats requires overcoming several obstacles, especially in the traditional maritime sector, where scepticism about new technologies is still a significant obstacle. Operators frequently worry about dependability problems, wondering if electric tugboats can withstand prolonged use or function adequately in harsh environments [22].

The absence of current infrastructure to support electric fleets is a significant obstacle. To manage the high energy demand of electric propulsion, many ports need to modernise their grids, including installing new transformers, cables, and energy storage devices [40]. These infrastructure expenses remain a significant barrier without industry-wide investments or government assistance, especially for smaller and growing ports.

Reliance on renewable energy is not without its difficulties. If ports depend on electrical grids that run on fossil fuels, the environmental advantages of electric tugboats are reduced [35]. To preserve sustainability, ports must invest in intelligent energy storage technologies that guarantee a steady, clean energy supply, even when renewable power generation is limited [41].

Another challenge is workforce adaptation, since operators and maintenance staff must receive specific training to operate high-voltage electric propulsion systems [22]. Long-term financial commitments are also risky, as many businesses put short-term profits ahead of long-term savings, which delays the adoption of electric fleets [40].

Finally, charging station placement and grid dependability must be carefully planned to avoid operational disturbances, especially in busy ports where delays could affect supply chains and logistics. Strategic investments in infrastructure, policy, and technology will be crucial to overcome these obstacles and guarantee a seamless transition to a more sustainable maritime sector.

Electric tugboats are a revolutionary development in the marine sector due to their significant cost savings, operating efficiency, and environmental advantages. However, the industry's opposition to change, infrastructure constraints, and hefty upfront expenses impede implementation. The maritime industry may effectively shift toward a more sustainable future by utilising technological developments, regulatory assistance, and integration of renewable energy sources. To guarantee broad acceptance and optimise the long-term advantages of electric tugboats, issues including battery constraints, charging infrastructure, and workforce training must be resolved.

Although the advantages of electric tugboats-such as lower emissions, cost savings, and increased efficiency-make a strong argument for their use, some obstacles still need to be overcome, such as expensive initial costs, battery constraints, and significant infrastructural improvements. To learn more about these benefits and difficulties from the viewpoint of the maritime industry, a focus group was held with maritime specialists. By examining operational issues, real-world experiences, and the viability of using electric tugboats in port and commercial operations, this conversation sought to validate the theoretical conclusions. The results of these interviews are shown in the following part, emphasising the viewpoints of industry representatives regarding the advantages and disadvantages of this technological shift.

5. Interviews with Industry Representatives

Focus groups are a qualitative research technique used to collect opinions from a limited number of subject-matter specialists. Finding specific and valuable facts entails a guided discussion to confirm or improve preexisting conclusions. The focus group's efforts to connect theoretical conclusions with practical industry experiences ensured a comprehensive and well-supported analysis [50].

Selected experts from the port and maritime industry participated in the focus group, including a captain, two university professors, two naval architects, one chief engineer of a tugboat with experience in energy storage, one representative of a naval policy-making body specializing in navigation safety, and two representatives from a towing service company.

At the start of the activity, a structured questionnaire was used to gauge participants' opinions on the topic's benefits and drawbacks (see Table 3). Respondents assigned a score to each question on a scale of 1 (not relevant) to 5 (very relevant).

The answers to the questionnaire were used to divide the conversations into two main sections:

1. Identification of Advantages: Participants explored key benefits, incorporating questionnaire responses and additional discussion insights.

2. Analysis of Disadvantages: This stage identifies challenges and limitations and comprehensively assesses the research topic.

The conversation aimed to encourage in-depth analysis based on preliminary data and stimulate the exchange of ideas. Using the questionnaire to determine points of agreement and disagreement, the focus group approach successfully verified and improved theoretical conclusions.

This adaptable strategy allowed for gathering quantitative and qualitative data while considering the participants' real-world experiences. Expert interactions from different fields enhanced the study by providing interdisciplinary viewpoints on business opportunities and challenges.

Table 3. *Questionaire*

Advantages	Disadvantages
1. The adoption of electric propulsion technology in tugboats leads to improved operational efficiency	1. Electric tugboats may have a limited range compared to diesel-powered vessels due to the capacity and weight of onboard batteries. This can restrict their operational flexibility, especially for long-distance towing or extended operations without recharging.
2. Electric tugboats improve air quality by eliminating emissions, benefiting workers' environment, health, and well-being in ports and nearby communities.	2. The initial investment in purchasing electric tugboats, including the necessary infrastructure for charging or battery replacement, can be higher than that of traditional diesel-powered tugboats.
3. Electric tugboats generally incur lower operating expenses than their diesel counterparts due to reduced maintenance requirements and fewer moving components, contributing to cost efficiency.	3. Charging electric tugboats can take significantly longer than refuelling diesel-powered vessels, leading to potential downtime and reduced productivity during charging cycles.
4. Electric propulsion systems typically boast higher energy efficiency levels than diesel engines, resulting in decreased energy consumption and lower fuel expenses.	4. Batteries required for electric propulsion systems can be heavy and bulky, impacting vessel stability and manoeuvrability due to additional weight and space constraints.
5. Electric tugboats can operate in sensitive areas such as nature reserves or near populated areas where strict emissions regulations or noise pollution must be minimised.	5. Electric propulsion systems may have lower power output than conventional diesel engines, particularly in high-demand situations such as towing heavy loads or manoeuvring vessels.
6. Electric tugboats can leverage advancements in energy storage technology, such as high-capacity batteries, to store energy during off-peak times or from renewable sources, enhancing operational efficiency and reducing reliance on grid power.	6. Electric tugboats rely on a stable and reliable electricity supply, which may be subject to disruptions, grid outages, or fluctuations in energy prices. This dependency introduces risks related to energy security and operational resilience.
7. Governments may offer incentives, subsidies, or tax breaks to encourage the adoption of electric propulsion technology, further enhancing the economic viability of electric tugboats.	7. Batteries in electric tugboats may experience reduced performance and efficiency in cold weather conditions.

The results emphasize the benefits and drawbacks of this new technology while fortifying the connection between theory and practice, and providing insightful information about the marine industry's adoption of electric tugboats.

According to most participants, the main benefit of electric tugboats is the decrease in greenhouse gas emissions. Industry representatives strongly emphasised this feature in light of strict emission standards and global goals for reducing carbon emissions. Participants underlined that ports with stringent air quality regulations benefit greatly from electric tugboats.

Discussions, however, showed that this benefit is highly dependent on the energy source. Electric tugboats have a significant positive environmental impact when their electricity is produced using renewable resources. On the other hand, if the energy source is dependent on fossil fuels, the beneficial ecological effect is significantly reduced. As a result, the environmental advantages of electric tugboats are directly related to the advancement of the worldwide green energy transition.

Another significant advantage of electric tugboats was lower operating expenses. Key economic benefits identified include the removal of traditional fuels and lower maintenance needs, ascribed to the ease of use of electric motors. According to industry officials, specific circumstances, like the tugboat's lifespan and the accessibility of charging infrastructure, make these cost advantages especially apparent.

Another benefit, according to some participants, is that electric tugboats can be used at ports with stringent restrictions or in environmentally sensitive areas. These vessels make it simpler to comply with environmental standards, which helps businesses that use them financially and reputationally reputation. They were also emphasized as representations of technological leadership, fostering innovation and sustainability, to give operators a competitive edge.

The limited range of electric tugboats, due to the present battery capacity, was one of the most commonly noted drawbacks among the respondents. Participants stated that these vessels are less appropriate for operations that require continuous availability or for long-duration operations. This restriction is considered a significant obstacle, particularly in ports without sufficient infrastructure for charging.

Throughout the discussions, the high initial investment needed to purchase and deploy electric tugboats was determined to be one of the biggest obstacles to their adoption. While long-term savings can partially offset these expenditures, many participants thought the high upfront costs and lengthy payback period were significant barriers, especially for small and medium-sized enterprises.

Another significant issue mentioned was electrical system maintenance, which necessitates specialist personnel who are hard to reach in some areas. This intricacy may result in extra expenses, and a shortage of qualified personnel may prevent broad adoption.

Many participants voiced concerns over battery technology, highlighting its short lifespan, high cost, and the environmental effects of its manufacture and recycling. According to them, technological developments in this field will determine the future of electric tugboats, and solutions needed to improve performance and lessen environmental effects.

The experts' comments show that electric tugboats are generally seen favourably, but they also point out important issues that must be resolved. Participants concurred that these ships have a great deal of promise to support environmentally friendly maritime transportation. Nevertheless, infrastructure, financial, and technological obstacles must be removed before they can be adopted.

According to the participants' answers, the following factors determine whether electric tugboats are successful:

- The construction of infrastructure for charging, especially in poorer nations and smaller ports;
- Developments in battery technology to increase cost-effectiveness, longevity, and range;
- Subsidies and policy support are required to lessen operators' upfront expenses;
- Renewable energy availability to optimise environmental advantages.

6. Conclusion and Recommendation

This study demonstrated how electric tugboats, with their substantial advantages including lower greenhouse gas emissions, less noise pollution, and increased operational and financial efficiency, have the potential to revolutionise the marine sector and make it more sustainable. However, other obstacles to their acceptance, such as large upfront expenditures, limited autonomy, and intricate infrastructure needs, remain.

The energy source these ships use mostly determines their environmental impact. The results show that ports that integrate renewable energy sources can greatly increase the benefits of these vessels. By incorporating electric tugboats into cutting-edge port systems, operations can be streamlined by reducing waiting times and resource usage.

Although switching to electric tugboats is crucial in creating a more sustainable and effective marine business, the public and corporate sectors must strongly support this change. The development of port infrastructure is priority one for the use of electric tugboats. Included in this procedure are:

- The placement of fast-charging stations in key ports;
- Electrical grid modernisation to accommodate rising energy demands;
- Including renewable energy sources integration, like wind turbines or solar panels.

Implementing tax breaks and subsidies can hasten the transition from a political and financial standpoint, and public-private partnerships can supply the funds required for research and infrastructure investment.

In terms of technology, it is imperative to make investments in:

- Batteries with a high energy density and quick charging;
- Intelligent systems for the best possible control of energy use.

Education and workforce development are also essential. To guarantee a trained workforce for the future of sustainable maritime transportation, initiatives such as specialist courses on the operation and maintenance of electric tugboats and partnerships with educational institutions to incorporate pertinent skills in training curricula are required.

Future studies should concentrate on increasing the operational range of electric tugboats, investigating other energy storage options such as hydrogen fuel cells, and assessing the incorporation of hybrid propulsion systems. Another crucial field is the creation of predictive management systems, which employ artificial intelligence-based maintenance models and energy demand forecast algorithms.

It is also necessary to continuously monitor how electric tugboats affect marine ecosystems by measuring the decrease in noise pollution in protected regions and by evaluating their effects on biodiversity. Thorough economic studies are also required to prove the long-term feasibility of electric tugboats, considering business models that share resources among port operators.

Through the implementation of these suggestions and further research, electric tugboats have the potential to be a key component of the shift to a more sustainable maritime sector, tackling economic issues while making a substantial contribution to environmental preservation.

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