systems

MDPI

*Article*

# Analyzing Carbon Regulation Impacts on Maritime Sector Using Fuzzy Delphi–DEMATEL–ISM Approach

**Ozan Hikmet Arıcan [1,*], Orçun Toprakçı [1], Ali Umut Ünal [2] and Gönül Kaya Özbağ [1]**

[1] Maritime Business Management Department, Maritime Faculty, Kocaeli University, Kocaeli 41500, Turkey; orcun402386@gmail.com (O.T.); gonul.kaya@kocaeli.edu.tr (G.K.Ö.)
[2] Maritime Transportation and Management Programme, Karamürsel Maritime Vocational School, Kocaeli University, Kocaeli 41500, Turkey; umut.unal@kocaeli.edu.tr
* Correspondence: ozanhikmet.arican@kocaeli.edu.tr; Tel.: +90-5448418417

**Abstract**

With the rapid increase in global trade in recent years, the demand for maritime transportation has significantly intensified vessel activity, leading to a considerable rise in carbon emissions originating from the maritime sector. As a result, in line with the 2050 decarbonization targets set by the International Maritime Organization (IMO) and the European Union (EU), legal regulations addressing carbon emissions have been dynamically tightened and gradually enacted. This study aims to determine the significance levels of the factors affecting the maritime sector in response to carbon emission regulations and to reveal the interrelationships among these factors. In this context, the criteria regarding the impacts of climate-related carbon emission regulations were identified based on expert opinions using the Fuzzy Delphi method. The interaction strengths and significance levels among the factors were analyzed using the Fuzzy DEMATEL method, and the relationships were modeled through Interpretive Structural Modeling (ISM). According to the findings, "Fuel Preferences and Alternative Fuel Usage" (C2) emerged as the most critical factor under recent international regulations. "Adaptation to International and National Regulations" (C8) and "Port Infrastructure" (C3) were also identified as the key factors impacting shipping industry efficiency. The analysis revealed that "Logistics Costs" (C5) and "Environmental Protection and Sustainability" (C7) are the most significantly affected outcome factors within the system. The hierarchical structural modeling revealed that "Port Infrastructure" (C3) serves as a defining starting point within the system. This study contributes to the literature by uncovering the causal relationships among the factors determining the effectiveness of ever-evolving carbon emission regulations. It offers a valuable decision-support tool for maritime companies and policymakers. Accordingly, it provides an alternative roadmap and a structural model indicating which strategic areas should be prioritized to achieve the targeted low-carbon emission goals in maritime transportation.

**Keywords:** carbon emissions; maritime business management; maritime transportation; fuzzy delphi; fuzzy DEMATEL; interpretive structural modeling (ISM)

check for updates

Academic Editor: Vladimír Bureš

Received: 22 August 2025
Revised: 21 October 2025
Accepted: 24 October 2025
Published: 27 October 2025

**Citation:** Arıcan, O.H.; Toprakçı, O.; Ünal, A.U.; Özbağ, G.K. Analyzing Carbon Regulation Impacts on Maritime Sector Using Fuzzy Delphi–DEMATEL–ISM Approach. *Systems* **2025**, *13*, 955. https://doi.org/10.3390/systems13110955

**Copyright:** © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Maritime transportation is the dominant mode of freight carriage in international trade, accounting for over 80% of global trade volume [1]. This extensive use has brought about significant environmental concerns, particularly with respect to carbon emissions resulting from maritime activities. Over the past decade, the share of carbon emissions from

maritime transport in total anthropogenic emissions has increased, It currently accounts for approximately 3% of global greenhouse gas (GHG) emissions [2].

The Initial IMO Strategy on the Reduction in GHG Emissions from ships was developed as early as 2018 [3], aiming to align with the goals of the Paris Agreement [4]. The strategy targets a reduction of at least 50% in GHG emissions from international shipping by 2050 compared to 2008 levels, with the ultimate goal of achieving net-zero emissions around mid-century [5]. In 2023, the IMO adopted the Revised GHG Strategy through MEPC 80, replacing the previous target of achieving net-zero emissions from international maritime transport around 2050 with a more ambitious goal [6,7]. In a similar manner, the European Union introduced Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023, aiming to achieve an 80% reduction in the greenhouse gas intensity of fuels used in the maritime sector by 2050 [8].

In this context, both the IMO and the EU have enacted a series of regulatory frameworks outlined in Figure 1 that define specific requirements and scopes to reduce GHG emissions in the maritime sector [9]. In line with the 2050 decarbonization targets, these regulatory efforts continue to expand. To comply with the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), and the Carbon Intensity Indicator (CII), or to take corrective actions in case of non-compliance, ships are required to implement an Energy Efficiency Management Plan. This plan includes operational measures such as fuel-saving strategies, draft and trim optimization, propeller and hull cleaning, speed optimization, and timely maintenance as outlined by Sun et al. [10] (EEDI), as well as technical measures such as wind-assisted propulsion, propeller optimization, and the use of alternative fuels [11]. Compliance with these standards and remedial actions is critical for reducing the environmental footprint of the maritime industry [12].

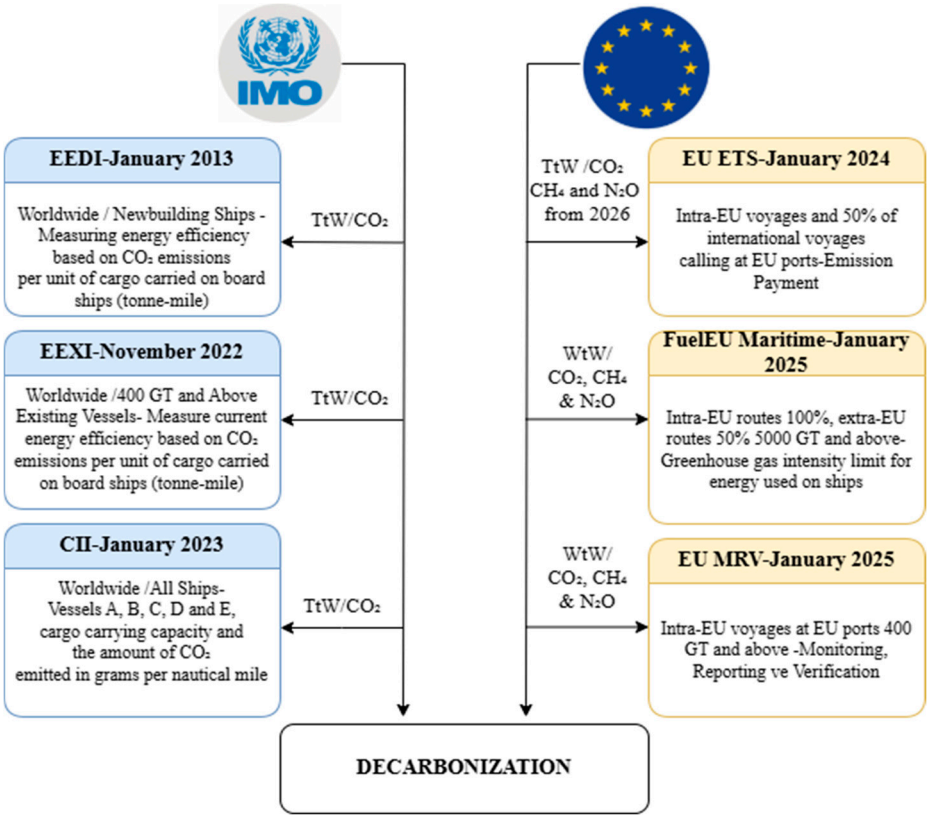



**Figure 1.** Regulations driving shipping industry decarbonization [9].

As of 1 January 2024, the European Union (EU) has included the maritime sector within the scope of the Emissions Trading System (ETS) [13]. However, numerous greenhouse gases have the capacity to influence the quality and efficiency of ETSs. The establishment and operation of a discrete emissions trading market for each greenhouse gas is a challenging undertaking [14]. FuelEU Maritime, on the other hand, establishes requirements for the annual average GHG intensity of ships operating in trade within the EU or the European Economic Area (EEA) [9]. This intensity is measured in grams of $CO_2$ equivalent per megajoule of energy ($gCO_2e/MJ$) and is calculated using the Well-to-Wake (WtW) approach [15].

In parallel, the EU Monitoring, Reporting and Verification (EU MRV) system, which also came into force on 1 January 2024, aims to assess the environmental impact of maritime transport and serve as the basis for determining carbon pricing under the EU ETS and FuelEU Maritime regulations [16]. EU MRV applies to ships of 5000 gross tonnage (GT) and above operating on voyages related to the EU. From 1 January 2025, revised EU MRV regulations will also cover general cargo ships between 400 and 5000 GT, as well as all cargo vessels of 400 GT and above [17].

The Net-Zero Framework (NZF) was finally approved in principle by the International Maritime Organization (IMO) at the 83rd session of the Marine Environment Protection Committee (MEPC), which took place from 7 to 11 April 2025. Final legal adoption is expected at the 84th MEPC session. Implementation is expected to begin in 2028, following the completion of ratification procedures by member states.

During the MEPC 83 session, decisions were made to implement a greenhouse gas intensity calculation mechanism globally, based on the WtW approach, similar to that used in the FuelEU Maritime regulation, as a complement to the existing Carbon Intensity Indicator (CII) metric. This regulation will involve the annual measurement of a ship's Greenhouse Gas Fuel Intensity (GFI) and the assessment of this intensity according to a two-tier reduction target system. Emission reduction requirements will be progressively increased each year based on the WtW approach, and these targets have been defined as the GFI Direct Compliance Balance Target (Tier I) and the GFI Base Target (Tier II). In cases of non-compliance, penalties will be imposed per ton of $CO_2$ equivalent ($CO_2eq$). According to the IMO, penalties will be imposed per ton of $CO_2$ equivalent ($CO_2eq$) in cases of non-compliance.

In this context, various regulations and policies recently implemented by international organizations such as the IMO and the EU, have led to multidimensional effects on the maritime sector through their interactions. In the literature, the impacts of these regulations on freight rates, logistics costs, ship operating expenses, the use of alternative fuels, port infrastructure, and shipowners' investment decisions have been examined using various methodological approaches. However, most of these studies have focused on a single aspect of impact, and relatively little attention has been paid to systematic, multi-criteria analyses of the regulations. Furthermore, the use of methods capable of visualizing influential relationships among impact criteria and weighing these relationships has remained limited. Therefore, it has been assessed that there is a need for more holistic and interaction-oriented analyses that take into account the complex and reciprocal effects of increasingly stringent carbon emission regulations introduced in recent years.

A review of the literature reveals numerous publications addressing the outcomes of policies aimed at reducing carbon emissions, which have become increasingly important in the maritime sector in recent years. However, it is evident that the majority of these studies are limited to a one-dimensional perspective. Many of studies underscore the significant impact of carbon emission regulations on various issues, including operational efficiency, ship energy performance, freight rate formation, and the adoption of alternative fuels.

For instance, while certain studies concentrate exclusively on the economic implications of carbon pricing and the compliance costs for shipowners, others explore technological solutions such as the design of energy-efficient ships or the enhancement of fuel propulsion systems. The extant literature provides valuable insights into the individual components of the decarbonization process. However, there is a general tendency to overlook the connections between regulatory, technical, financial, and infrastructural dimensions. Existing studies have not adequately addressed the systemic nature of maritime decarbonization, whereby changes in one factor can create cascading effects in others.

Previous studies have relied on descriptive or partial quantitative analyses, which fail to adequately represent the complex causal mechanisms driving sectoral compliance with carbon regulations. The absence of an integrated framework renders it challenging to assess how strict regulatory rules simultaneously affect multiple performance areas, including logistics cost structures, investment strategies, port readiness, and environmental outcomes. In this regard, the absence of an approach that combines expert-based assessment with causal and hierarchical modeling to represent the multidimensional and interdependent nature of these factors is a significant gap in the literature. To address this gap in the literature, the present study proposes an integrated analytical framework based on the Fuzzy Delphi–Fuzzy DEMATEL–ISM methodology. The aim of this framework is to systematically identify, weight, and model the interrelationships among the key criteria affecting the maritime sector under increasingly stringent carbon emission regulations. Within this framework, the study aims to identify the criteria related to the impact of carbon emission regulations on the maritime sector using the Fuzzy Delphi method and to analyze these criteria based on expert opinions. Moreover, the objective of the present study is to utilize the Fuzzy DEMATEL method to elucidate the causal relationships between the factors. Furthermore, given the multidimensional effects of multiple criteria, the study aims to use the Interpretive Structural Modeling (ISM) technique to develop an impact-relationship map at the sectoral level and to create an impact model, based on this map.

The structure of the study is as follows. First, Section 2 presents a comprehensive literature review examining the impacts of carbon emission regulations from various perspectives. Next, Section 3 summarizes the scientific methods employed in the research, including the Fuzzy Delphi and Fuzzy DEMATEL techniques, and provides an overview of the ISM analysis. Subsequently, Section 4 presents the findings and the developed modeling framework. Following this, Section 5 discusses and interprets the implications of the results. Finally, Section 6 offers insights and recommendations for future research on the effects of carbon emission regulations on maritime transportation.

## 2. Background

Recent years have witnessed a growing interest in understanding the multifaceted impacts of carbon emission regulations on the maritime sector. International regulations, particularly those introduced by the IMO and the EU, have spurred numerous studies analyzing their effects across various dimensions. The literature predominantly focuses on several key areas, which are systematically reviewed below.

### *2.1. Freight Rates, Logistics Costs, and Ship Operating Expenses*

The potential impacts of carbon taxation on maritime trade have been extensively evaluated in the extant literature. For instance, Wu et al. [18] assessed these impacts by developing a bulk carrier model and found that the implementation of carbon taxation could lead to significant increases in freight rates (between 10% and 30%) and commodity prices.

In a similar vein, Rojon et al. [4] established that the implementing of carbon pricing exerts a modest influence on the overall maritime transport costs of the most nations with diverse trade structures reliant on maritime. Some contend that the phenomenon may exert a deleterious effect on small island developing states and least developed countries, which have relatively low trade volumes and are acutely sensitive to increases in unit shipping costs. This is because shipping costs constitute a larger proportion of their import and export expenditures.

Takebayashi [19] investigated the impact of carbon taxation and vertical integration between shipping companies and ports on supply chain performance and overall economic welfare in the maritime sector. The study demonstrated that vertical integration positively affected consumer surplus by improving port service quality and reducing emissions per unit.

In another study, Ding et al. [20] conducted a comparative economic analysis between the Northern Sea Route (NSR) and the Suez Canal Route (SCR) under fixed and progressive carbon tax scenarios. Their findings revealed that, regardless of fuel type, the NSR is economically advantageous when either no carbon tax or an equal tax on both routes is applied. Furthermore, it was found that a progressive carbon pricing strategy is more beneficial than a fixed strategy and that liquefied natural gas (LNG) is an attractive fuel option compared to other options due to its lower unit cost.

Cario et al. [21] examined the effects of maritime fuel taxes on shipowners' profits, international trade, and emissions, utilizing data from 2016. The researchers proposed that fuel taxes exceeding USD 100 per ton might be required to achieve a substantial reduction in carbon emissions.

Similarly, Mundaca [22] used econometric analysis in his study to assess the impact of carbon taxes on the prices of internationally traded goods transported by sea. The study showed that the closer an exporting firm is to its core competency (defined as the lowest marginal production cost), the less impact the carbon tax has on product prices.

Finally, Jin et al. [23] proposed an innovative collaboration-based emission reduction mechanism in their study and analyzed the results of this mechanism under three different scenarios: no collaboration, traditional collaboration, and collaboration involving information sharing. The results showed that the level and quality of collaboration among stakeholders play a critical role in determining the effectiveness and benefits of emission reduction strategies.

### *2.2. Environmental and Sustainability Aspects*

Kotzampasakis [24] emphasizes in his study that the EU Emissions Trading System (EU ETS) has the potential to achieve significant reductions in emissions at a lower total cost compared to other regulatory alternatives. The study demonstrates that the EU ETS can achieve significant emission reductions at a lower total cost compared to regulatory alternatives. Similarly, Park et al. [9] comprehensively analyze the impact of regulatory instruments such as the Carbon Intensity Indicator (CII), the EU ETS, and FuelEU Maritime on operating costs and emissions, highlighting their interrelated effects. The study concludes that, to achieve the intended outcomes of environmental policies, it is necessary to develop effective maritime regulations that align with the operational strategies of shipping companies and to adopt a holistic approach.

In the context of WtW greenhouse gas emission reductions, Oh et al. [5] demonstrate that carbon capture systems can reduce total GHG emissions by approximately 54% to 68%, representing a significant mitigation potential. Wang et al. [7], in their study on the effects of Emission Control Area (ECA) regulations, found that route deviation behaviors are inevitable under these constraints, often resulting in increased overall carbon emissions due to longer distances or suboptimal operational patterns.

Wu et al. [18] conducted a systematic review of relevant studies sourced from Scopus and Web of Science databases, synthesizing the driving forces, challenges, and potential impacts associated with implementing a Carbon Emission Trading System in the maritime sector. Their findings underscore both the opportunities and limitations of such market-based mechanisms. Finally, Sun and colleagues [10] examined how shipping companies operating on the China-Europe trade route could mitigate the financial burden imposed by carbon pricing programs. The findings indicate that prudent oversight of vessel velocity and voyage duration resulted in reduction of 1124 tons of carbon emissions within the context of the carbon tax policy scenario. Conversely, the carbon trading rights scenario gave rise to an increase in the annual number of voyages (5.30 as opposed to 5.24).

### 2.3. Alternative Fuel Use

In the context of decarbonization efforts, the adoption of alternative fuels has emerged as a key strategy within the maritime industry. Recent studies have addressed this topic from multiple perspectives, including environmental performance, economic feasibility, and technological readiness. For instance, Hellström et al. [25] explored the variations across different maritime segments regarding short- and long-term preferences for alternative fuels, highlighting that the transition towards cleaner energy sources is unlikely to follow a one-size-fits-all model. Complementing this, Rojon et al. [3] examined the production methods of green fuels such as green hydrogen, green ammonia, and green methanol, and assessed their potential implementation in maritime transport. Despite the promising outlook for green fuel, it is anticipated that, in the near term, its costs will exceed those of conventional fuels. It is concluded that there is a necessity to increase fuel production capacity to strengthen research and development in renewable energy and green fuel production technology, and to ensure a sufficient supply of low and zero-emission marine fuel.

A number of studies have also analyzed the economic implications of alternative fuel adoption. For instance, He et al. [13] demonstrated that a ship consuming 2000 tons of LNG annually could benefit from EU ETS allowance savings ranging from USD 10,000 to USD 20,000, illustrating the dual benefit of environmental gains and cost-efficiency.

Beyond technical and economic considerations, the importance of multi-technology integration is increasingly emphasized in achieving decarbonization targets. Issa et al. [26] suggested that the goals set by the IMO and the EU could only be met through the combination of two or three complementary technologies or through a radical technological shift offering highly efficient solutions. In a similar vein, Rony et al. [27] reviewed various potential pathways and technologies to assist the maritime sector in its transition to carbon neutrality. Empirical studies provide further insight into the tangible effects of alternative fuel use. Sjerić et al. [28] reported a 14–16% reduction in the carbon footprint and a 9.5–13.8% decrease in total operating costs for fishing vessels powered by LNG, demonstrating the practical viability of clean fuel options.

However, while the environmental benefits of alternative fuels are clear, operational and technological constraints remain a concern. Xing et al. [29] conducted a technical review to identify the most promising alternative marine fuels in terms of simultaneously reducing $SO_x$, $NO_x$, and $CO_2$ emissions and enhancing overall sustainability. Hydrogen and ammonia, which are zero-carbon synthetic fuels, have the potential to play a vital role in domestic and short-distance maritime transport when produced cleanly. However, current costs and infrastructure have been found to be commercially unviable. Following a comprehensive review of the extant literature, it was concluded that methanol (fossil/renewable), renewable natural gas, bioethanol, biogenic dimethyl ether and biodiesel are the most promising alternative fuels for global maritime transport. Cullinane et al. [30]

reinforced the idea that alternative zero-carbon fuels could be the most suitable long-term solution but concluded that operational and technological innovations alone would be insufficient to achieve full decarbonization without comprehensive policy support and infrastructure development.

### 2.4. Adaptation to International and Legal Regulations

Dong et al. [16] examined the legal and policy framework designed to facilitate the decarbonization of maritime transport and then proposed a series of development principles to analyze these policies, to comply with the principle of common but differentiated responsibilities, to coordinate the relationship between international trade and international environmental protection, and to provide technical assistance to developing countries. (reviewer 1—comment 2) Chen et al. [31] conducted a quantitative examination of extant research on decarbonization, utilizing bibliometric analysis techniques. Despite the ongoing evaluation and discussion of market-based measures, existing literature suggests that price control approaches (e.g., carbon tax) may be preferable to quantity control approaches (e.g., ETS) in consideration of the intricacies of policy design, administrative burden, regulatory consistency, carbon market stability, and incentives for technological innovation. Hero et al. [32] have conducted a comprehensive evaluation of greenhouse gas emission reduction practices in the maritime transport sector. The study concluded that the energy efficiency of new and existing ships, the ship index, and the carbon intensity of ships play an important role in reducing emissions. Furthermore, it was determined that various methods exist to reduce these indices, with older ships able reduce their emission index by lowering engine speed.

Peng et al. [33] conducted frequency analysis and causal research on container ships sailing around the Cape of Good Hope. The findings indicate that the current policy framework under the EU-ETS increases the risk of carbon leakage, particularly for medium and small-sized container ships, thereby weakening the effectiveness of the newly emerging EU maritime carbon pricing mechanism. Gössling et al. [34] emphasized that the majority of policies are voluntary or incentive-based at the port level, and that policies promoting or mandating the transition to zero-carbon fuels are required.

### 2.5. Investment Decisions and Competitiveness of Shipowners and Operators

Several recent studies have explored the implications of international and regional carbon regulations on maritime transport from legal, economic, and operational perspectives. A key area of concern is the legal uncertainty surrounding investor protections under schemes such as the EU Emissions Trading System (EU-ETS). As Wang et al. [35] highlighted, the potential for investment disputes to arise from provisions designed to protect investors against expropriation and to safeguard their legitimate expectations within the framework of the EU-ETS is a matter of significant concern. It has been determined that the potential risks of disputes related to the new EU directive in the global maritime sector can be effectively mitigated by specifying public purpose and exception clauses in the preambles of International Investment Agreements. Furthermore, it is recommended that the special obligations of foreign investors and the regulatory powers of host states be included in the draft stage.

The issue of double carbon pricing in maritime transport has also been addressed. Dominioni et al. [36] analyzed the potential advantages and disadvantages of overlapping emissions pricing mechanisms and discussed strategies to mitigate associated adverse impacts. The article concludes that a balance must be struck between competing interests, contextual factors and tool design in order to prevent dual pricing.

From an investment standpoint, Trosvik et al. [37] emphasized the influence of emission regulations on shipowners' investment decisions, suggesting that regulatory clarity and consistency are vital for encouraging green investments.

Broader research priorities have been outlined to guide future efforts. Govindan et al. [38] proposed key technical, economic, and policy research agendas necessary to achieve an effective and equitable transition toward net-zero emissions in maritime transport. The findings of this study have indicated that the most critical research priorities for the transition to net-zero shipping are the cost–benefit analysis of port initiatives, the techno-economic aspects of alternative fuels and carbon capture technologies, and the climate, economic, and socio-political impacts of carbon pricing.

In a sector-specific assessment, Flodén et al. [39] examined the cost implications of the EU-ETS and warned that if these costs are passed on to shippers without adequate mitigation strategies, they could lead to carbon leakage. The study also pointed out that in RoRo and RoPax segments, where modal shifts to road or rail are more feasible due to direct competition, maritime transport may lose ground to other transportation modes.

Competitive dynamics within supply chains have also been analyzed. Wang and Zhu [40] evaluated how carbon tax policies shape the maritime supply chain through both competitive and cooperative incentives among carriers. Numerical analyses indicate that, while the contract mitigates the impact of the carbon tax, fostering deeper inter-firm cooperation represents a more effective policy option for the government. Meng et al. [12] found that the most effective strategy for mitigating carbon emissions in the shipping industry involves the implementation of active government regulations and subsidies, combined with enhanced emission reduction initiatives by port and shipping enterprises.

Finally, Lugovskyy et al. [2] warned of the unintended consequences of emission limits, particularly the potential shift to more carbon-intensive transport modes such as aviation and trucking, which could result in an overall increase in $CO_2$ emissions in both the short and long term.

### *2.6. Port Infrastructure*

Recent research highlights the critical role of port infrastructure in supporting greenhouse gas emission reduction strategies within the maritime sector. However, the effectiveness of existing incentive schemes remains questionable. Alamoush et al. [41] found that many current programs aimed at encouraging emission reductions in ports and among shipping companies are burdensome and suffer from low adoption rates by these stakeholders. Operational innovations at the port level have also been explored as a means of enhancing environmental performance. Jia et al. [42] examined the implementation of "Just-In-Time" (JIT) arrival strategies at ports and demonstrated their potential to significantly reduce fuel consumption and emissions, offering a practical pathway toward more sustainable maritime logistics.

Nonetheless, regulatory measures such as carbon taxation may have unintended economic consequences. Song et al. [43] reported that imposing a carbon tax could reduce container handling volumes at ports, thereby lowering profits for both port authorities and shipping firms. It has been determined that the implementation of a carbon tax on ports results in a reduction in container handling volumes and profits. However, it is recommended that the government prioritize the taxation of shipping companies in order to optimize the achievement of its objectives. Furthermore, it is advised that ports adopt limited non-cooperation strategies.

Through case analyses of leading global ports, Wan et al. [6] illustrated how ports can position themselves as hubs of innovation in sustainable maritime logistics, emphasizing the need for integrative planning, technological adoption, and collaborative governance.

### 2.7. Research Gaps and Objectives

Although carbon emission regulations have become an increasingly prominent topic within the maritime sector, existing literature predominantly focuses on unidimensional impacts. Systematic analyses that comprehensively evaluate the effects of evolving and current emission regulations, particularly in light of recent IMO carbon tax proposals and newly implemented EU policies, remain limited.

The practical necessity of assessing these effects has been considered from two perspectives. IMO, an international body, and EU, a political and economic union, apply carbon taxes to reduce greenhouse gas emissions from global maritime transport. The implementation of such taxes is accompanied by a multitude of ramifications, encompassing economic, operational and environmental dimensions, which are intricately intertwined with other market-based instruments. Without a comprehensive and integrated understanding of these interactions, shipping companies and policymakers risk making decisions that could lead to unintended consequences, such as carbon leakage.

Secondly, the absence of thorough, multi-criteria impact evaluations impedes the development of effective, data-driven decarbonization strategies. The present study identifies and analyses the causal relationships between critical factors such as operational costs, investment decisions, the adoption of alternative fuels, port infrastructure, competitiveness and environmental sustainability. Furthermore, an impact-relationship map is presented at the sector level. This map functions as a valuable decision support tool, assisting shipping companies in prioritizing strategic areas and enabling policymakers to design more effective and equitable regulations. Consequently, addressing this research gap is imperative for facilitating a more methodical, balanced and inclusive transition towards a low-carbon shipping sector.

A comprehensive examination of the literature on the repercussions of carbon regulations on the shipping sector has been undertaken, focusing on multiple aspects. These vantage points encompass such areas as freight rates, the adoption of alternative fuels, and investment decisions. However, a significant gap remains in the literature concerning studies that analyse the multidimensional and interrelated nature of these effects in a holistic manner.

The present study addresses a significant research gap by offering a comprehensive and integrated analytical framework that combines Fuzzy Delphi, Fuzzy DEMATEL, and ISM methodologies. This framework is employed to analyze the multidimensional effects of carbon emission regulations on the maritime sector. Addressing this gap, the present study seeks to analyze the interrelationships among the key criteria affecting the maritime industry through expert opinions, employing a systematic methodological framework.

Organizations such as the IMO and the EU are actively planning and implementing market-based measures, including carbon taxes, to reduce greenhouse gas emissions from maritime transport. However, the economic, operational, and environmental impacts of such regulations are complex and characterized by strong interactions among various factors. Therefore, this study aims to identify and analyze the most critical criteria influencing the maritime sector's response to carbon emission regulations, using the Fuzzy DEMATEL-ISM approach to uncover the causal relationships between these factors. In doing so, the research considers multiple dimensions—including operational costs, investment decisions, alternative fuel adoption, port infrastructure, competitiveness, and environmental sustainability—to develop a sector-level impact-relationship map that provides a comprehensive understanding of the systemic effects of emission regulations.

## 3. Methodology

### *3.1. Research Methodology*

The Fuzzy Delphi method, the inaugural step in the methodology, constitutes a systematic and efficacious approach for achieving consensus among experts in identifying key influencing factors [44]. This method provides an iterative process for evaluating the importance of factors and their potential future impacts, thereby enabling the review of opinions and minimizing differences, thus enhancing the reliability of the results [45]. The integration of quantitative data with expert knowledge and judgment has been identified as a hallmark of this hybrid method [46]. The Fuzzy Delphi technique is frequently utilized as a preliminary step in multi-criteria decision-making (MCDM) methods, including DEMATEL, AHP, ISM, and VIKOR, functioning as a potent instrument for identifying and prioritizing criteria to be employed in subsequent analyses [47]. In this study, the identification of impact factors was conducted using the Fuzzy Delphi method which incorporated expert opinions.

The extant literature presents a variety of mathematical approaches that are designed to provide decision-makers with support in the context of MCDM problems. Such approaches include AHP (Analytical Hierarchy Process), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje), ELECTRE (Elimination and Selection Reflecting Reality), GRA (Grey Relational Analysis), and BWM (Best-Worst Method). In comparison to these, the DEMATEL method developed by Gabus and Fontela is distinguished by its capacity to visualize the mutual relationships between factors through influence-relationship maps, analyze complex influence-outcome dynamics, and assign weights to criteria simultaneously [46]. Fuzzy-based methods have been shown to compensate for minor differences in expert responses, incorporate uncertain and hesitant judgements more realistically, achieve stronger consensus, and reduce uncertainties [48].

The DEMATEL method is a quantitative approach that determines and visually presents the interactions and cause-effect relationships between criteria. Interpretative Structural Modeling (ISM) is a method of transforming these relationships into a hierarchical and structural model for better visualization [49]. In this study, ISM was applied following the Fuzzy DEMATEL analysis. These two methodological approaches are widely accepted as complementary and powerful tools [49–51]. The methodology, incorporating Fuzzy Delphi, Fuzzy DEMATEL, and ISM methods, is presented schematically in Figure 2.

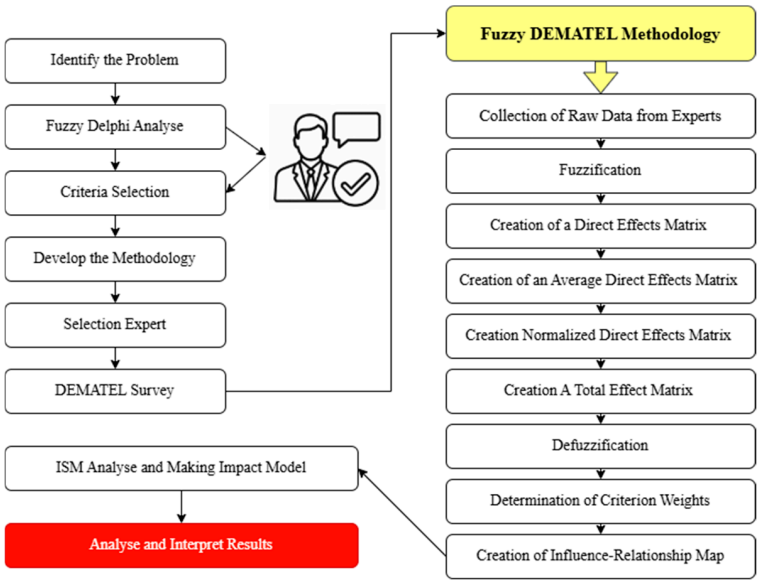



**Figure 2.** Framework of research methodology.

### 3.2. Population and Sample of the Study

The Delphi and DEMATEL methods are particularly well-suited for analyzing survey data collected from expert groups [52]. Accordingly, the data for this study were collected via surveys administered to personnel working at leading maritime companies in Turkey's shipping sector. The population of this study comprises all maritime transportation companies involved in shipping activities, which represent the largest affected group.

For sample selection, a purposive sampling technique was adopted to reflect the research problem and to capture the most typical scenarios for problem-solving.

Given that responding to the survey requires expertise and experience, the sample was composed of professionals with at least 10 years of experience at managerial levels in maritime companies. The characteristics of the experts who participated in the survey are presented in Table 1.

**Table 1.** Profile of the experts participating in the study.

| Experts | Experience (Years) | Duty | Ship Type | Education |
|---|---|---|---|---|
| Expert 1 | 15 | Technical Manager | Dry Cargo | Licence |
| Expert 2 | 13 | Marine Planner | Container | Master's Degree |
| Expert 3 | 17 | Operation Manager | Tanker | Master's degree |
| Expert 4 | 25 | Designated Person Ashore (DPA) | General Cargo | Licence |
| Expert 5 | 18 | Safety Quality Manager | Chemical Tanker | Licence |
| Expert 6 | 12 | Marine Superintendent | Chemical Tanker | Licence |
| Expert 7 | 13 | Operation Manager | Tanker | PhD |
| Expert 8 | 25 | Designated Person Ashore (DPA) | General Cargo | Licence |
| Expert 9 | 24 | Operation Manager | Dry Cargo | Licence |
| Expert 10 | 18 | Technical Manager | Chemical Tanker | Master's Degree |
| Expert 11 | 20 | Operation Manager | Dry Cargo | Licence |
| Expert 12 | 11 | Marine Planner | Dry Cargo | Licence |

Due to the complex structure of the maritime sector and its interconnectedness with various factors, national and international maritime authorities often rely on expert opinions to analyze the impacts of new regulations after their implementation and to address arising challenges. Therefore, maritime experts play a crucial role in providing data regarding the activities of the IMO or other maritime authorities and the effects of their regulations.

While experience is generally accepted as the primary criterion for identifying experts in the sector, consulting individuals from diverse fields within maritime activities offers a broader perspective [53]. Accordingly, when selecting decision-makers for this study, attention was given not only to their experience but also to the need to ensure representation from different functional areas within the maritime industry.

Although a sample size of twelve experts may be considered modest in some quantitative research frameworks, it is a widely accepted and methodologically appropriate application in the field of expert-based survey methodologies, especially when MCDM techniques such as Fuzzy Delphi and DEMATEL [54–56] are used. The robust structure of these methods, which rely on the in-depth knowledge and qualitative insights of highly experienced professionals, typically requires a smaller, high-quality panel of experts rather than a large, generalizable survey sample. This approach prioritizes the depth and quality of expert judgment over statistical representativeness to provide strong and qualitative input for the pairwise comparisons required by DEMATEL, as individual expert opinions carry significant weight and directly contribute to the development of a robust decision

model. As summarized in Table 1, the careful selection of experts ensures that the collected data reflects a high level of domain-specific expertise, thereby strengthening the reliability and validity of the findings within the context of existing research norms for such methodologies.

### *3.3. Fuzzy Delphi Method*

The traditional Delphi method aims to achieve consensus on complex issues by gathering expert opinions through successive rounds of surveys [25]. Generally, the Delphi process consists of five main steps, in which criteria are gradually reduced through multiple rounds among expert groups until the strongest factors are selected [57]. However, the repeated surveys and pressure to revise opinions can negatively affect the consistency of expert judgments [58].

Fuzzy Set Theory, developed by Zadeh in 1955, provides a way to capture uncertainty and transform qualitative expert language into quantitative values [59]. Integrating this theory with the Delphi method has reduced the number of survey rounds and shortened the research duration, while enabling a more comprehensive expression of expert evaluations [44]. The fuzzy Delphi model offers advantages over the classical Delphi by decreasing the number of rounds and research time, thus enhancing the consistency of expert opinions [60].

Step 1—Creation of the Fuzzy Delphi Questionnaire: The fuzzy approach converts expert opinions expressed in linguistic terms into fuzzy numbers; in this study, Triangular Fuzzy Numbers (TFNs) were preferred. TFNs are represented by three real numbers: the minimum possible value (a), the most likely value (b), and the maximum possible value (c) [58]. To determine the impact levels of the final identified criteria, a questionnaire was designed using the linguistic variables shown in Table 2 [61].

**Table 2.** List of linguistic terms and meanings.

| Symbols | Linguistic Variables | TBSs (a, b, c) |
|---|---|---|
| VL | Very Low Efficiency | (0, 0, 0.25) |
| L | Low Efficiency | (0, 0.25, 0.5) |
| M | Medium Efficiency | (0.25, 0.5, 0.75) |
| H | High Efficiency | (0.5, 0.75, 1) |
| VH | Very High Efficiency | (0.75, 1, 1) |

Step 2—Calculation of Average Fuzzy Evaluation Scores: The average fuzzy evaluation score for each factor is calculated using Equation (1). This calculation assumes that the estimated value for the $j$-th factor is provided by the $i$-th expert among a total of $n$ experts [45].

$$\widetilde{\omega}_{ij} = \left(a_{ij}, b_{ij}, c_{ij}\right), \;\; i = 1, 2, 3 \ldots . n, \;\; j = 1, 2, 3 \ldots . m \tag{1}$$

The average of the fuzzy numbers ($\widetilde{\omega}_{ij}$) corresponding to the $j$-th factor is obtained using Equation (2).

$$\widetilde{\omega}_{j} = \left(a_{j}, b_{j}, c_{j}\right), \left(\frac{1}{n}\sum_{i=1}^{n} a_{ij}, \;\; \frac{1}{n}\sum_{i=1}^{n} b_{ij}, \;\; \frac{1}{n}\sum_{i=1}^{n} c_{ij}\right), \; j = 1, 2, 3 \ldots . m \tag{2}$$

Step-3—Determination of the Most Influential Criterion: During the defuzzification process, the average fuzzy evaluation score ($\widetilde{\omega}_{j}$) for each $j$-th factor is converted into a crisp

value. The aggregated fuzzy scores ($S_j$) of the factors are defuzzified using the simple center of gravity method as proposed by Mohammadfam et al. [62], as shown in Equation (3).

$$S_j = \frac{a_j + b_j + c_j}{3}, \text{ j} = 1, 2, 3 \ldots \text{m} \tag{3}$$

The evaluation scores ($S_j$) were used to determine the ranking of the factors in terms of importance. Factors with a score of 0.7 or above were considered effective, while the others were excluded from the study [59].

The acceptability of the estimation domain was examined by calculating the difference ($D_{ij}$) between the average fuzzy number ($\widetilde{\omega}_j$) for the $j$-th factor and each expert's fuzzy estimate ($\widetilde{\omega}_j$), using Equation (4).

$$D_{ij} = \sqrt{\frac{1}{3}\left[ \left(a_j - a_{ij}\right)^2 + \left(b_j - b_{ij}\right)^2 + \left(c_j - c_{ij}\right)^2 \right]} \tag{4}$$

Each threshold value (D) for the $j$-th factor is calculated using Equation (5).

$$d = \frac{1}{n} \sum_{i=1}^{n} D_{ij} \tag{5}$$

The threshold value ($Th_d$) of each estimation domain is checked using Equation (6).

$$Th_d = \frac{1}{n} \sum_{i=1}^{m} d_j \tag{6}$$

The acceptability of the estimation domain is determined by the value of $Th$. In this study, the estimation domain is considered acceptable if the eror $Th_d \leq 0.2$ [47].

Expert group consensus $EA_j$ is tested for each factor by calculating expert agreement using Equation (7) [59].

$$EA_j = \frac{E_j}{n} \tag{7}$$

Here, $n$ denotes the total number of experts, and $E_j$ represents the distance between the fuzzy estimation values of experts ($\widetilde{\omega}_j$) for a specific factor $j$ and the average fuzzy number ($\widetilde{\omega}_j$) for that factor across all experts. If this distance is $\leq$0.2, expert group consensus is evaluated based on the criterion that $EA_j \geq 75\%$ of experts indicate sufficient agreement for that factor. Otherwise, factors with less than 75% expert consensus are excluded from the study [52].

### *3.4. Fuzzy Dematel Method*

The DEMATEL method was introduced in 1972 by Gabus and others to analyze interactions among variables. DEMATEL relies on expert opinions and converts linguistic assessments into fuzzy numbers using TFNs. This transformation aims to reduce uncertainty and facilitate consensus among experts. In 2008, Lin [63] applied DEMATEL in a fuzzy environment. Fuzzy DEMATEL identifies driving and dependent criteria by minimizing uncertainties in the relationships between criteria and sub-criteria [64].

Classical DEMATEL evaluates the relationships among decision factors based on crisp values and constructs a structural model. However, human judgments used in many studies tend to be uncertain and are challenging to quantify with exact numerical values. Additionally, estimating the uncertainty among these criteria is difficult. Therefore, many researchers have integrated fuzzy logic methods into the DEMATEL approach [54]. Fuzzy Logic-Based DEMATEL is developed by incorporating "fuzzification" and "defuzzification" processes into the classical DEMATEL [65].

Fuzzy DEMATEL is widely applied in various fields such as risk analysis, safety management, and human resource management [66]. In this study, the Fuzzy DEMATEL method was applied by following the steps below, with the detailed computational formulas provided in Appendix A.

Step-1—The collection of Expert Judgments: A total of k selected experts are asked to assess the extent to which factor $F^i$ influences factor $F^j$ among a set of *n* predefined factors. The evaluations are conducted using a five-point Likert-type scale, defined as follows:

Very Highly Influential = 5, Highly Influential = 4, Moderately Influential = 3, Slightly Influential = 2, Not Influential = 1.

Step-2—Conversion of Linguistic Data into Fuzzy Values (Fuzzification): To convert the linguistic data provided by participants into fuzzy values, various triangular fuzzy number sets developed by [67,68], and [63] have been used in the literature. In this study, triangular fuzzy numbers proposed by [63] have been adopted because they are simple, fast, easy to interpret, and widely used. These values are shown in Figure 3, and the corresponding fuzzy numerical representations of linguistic terms are presented in Table 3.

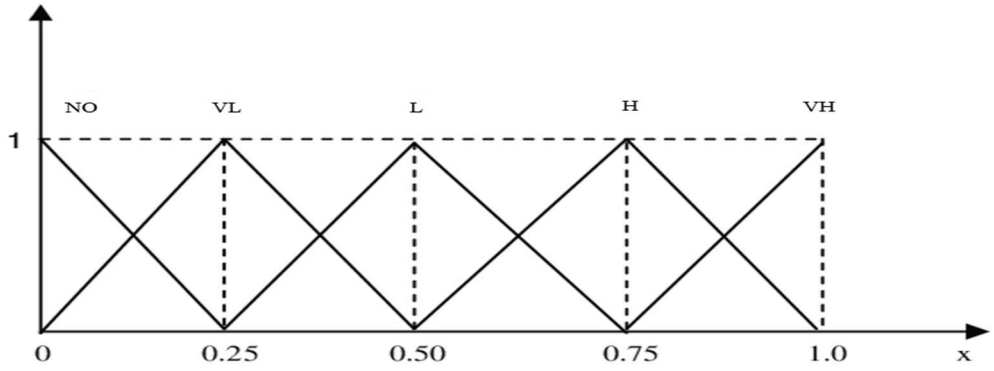



**Figure 3.** Triangular fuzzy numbers.

**Table 3.** Fuzzy number equivalents of linguistic expressions.

| Linguistic Terms | Code | Fuzzy Number |
|---|---|---|
| Very Highly Influential | VH | (0.75, 1.0, 1.0) |
| Highly Influential | H | (0.5, 0.75, 1.0) |
| Moderately Influential | L | (0.25, 0.5, 0.75) |
| Slightly Influential | VL | (0, 0.25, 0.5) |
| Not Influential | No | (0, 0, 0.25) |

For instance, the term "Slightly Influential" is represented by a triangle defined by fuzzy numbers (0.0, 0.25, 0.5). This configuration provides a visual foundation for the process of fuzzyfication, which involves converting experts' linguistic assessments into quantitative fuzzy values. The employment of TFNs facilitates the encapsulation of the inherent uncertainty and imprecision that characterize human judgment.

Step-3—The Creation of a Direct Effects Matrix ($\widetilde{Z}^k$): Based on the influence evaluations of factor $F_i$ on factor $F_j$ among $n$ factors collected from $k$ selected experts, individual direct effect matrices $\widetilde{Z}^k = \left[\widetilde{z}_{ij}^k\right]_{nxn}$ are constructed. $\widetilde{Z}^k$ is an $n \times n$ matrix obtained through pairwise comparisons representing the effects of the criteria on each other. Here, (Equation (A1)) $\left[\widetilde{z}_{ij}^k\right]$, $i$ denotes the degree to which criterion i influences criterion $j$ [65].

Step-4—The Creation of an Average Direct Effects Matrix ($\widetilde{Z}$): The arithmetic mean of the individual direct effect matrices results in the average direct effect matrix $\widetilde{Z} = \left[\widetilde{z}_{ij}\right]_{nxn}$ which incorporates the opinions of all experts (see Equation (A2)) [63].

Step-5—Creating Normalized Direct Effects Matrix ($\widetilde{X}$): The normalized matrices are obtained by applying Equations (A3) and (A4) [48].

Step-6—Creating A Total Fuzzy Effect Matrix ($\widetilde{T}$): Using Equations (A5)–(A10), the total relationship matrices $\widetilde{T} = \left[t_{ij}\right]_{nxn}$ are derived from the normalized direct effect matrices [44].

Step-7—Defuzzification: The defuzzification process, which converts fuzzy numbers into crisp values (Equation (A10)), is one of the most critical steps in the DEMATEL method [69]. The Converting Fuzzy Numbers into Crisp Scores (CFCS) technique, developed by Lin [63], offers advantages over other defuzzification methods, particularly in distinguishing symmetric triangular fuzzy numbers. Studies have demonstrated that CFCS can be effectively applied in MCDM models. Furthermore, CFCS is effective not only within the DEMATEL framework but also proves useful in other MCDA methods for converting fuzzy numbers into precise values. The related formulas are presented in Equations (A11)–(A16).

Step-8—Determination of Criterion Weights: Using Equations (A17) and (A18), the row sums $D = [d_i]_{nx1}$ $R = \left[r_j\right]_{1xn}$ and the column sums of the total defuzzified relationship matrix are obtained. The weights of the criteria, ranging between 0 and 1, are calculated using Equations (A19) and (A20). Naturally, the sum of the criteria weights equals 1 [52].

Step-9—The Creation of the Influence-Relationship Map: For each factor, the values of (D + R) and (D − R) are calculated to create the influence-relationship map. An increase in the (D + R) value indicates a rise in the importance of the criterion, while a positive (D − R) value signifies that the criterion belongs to the influencing group, and a negative value indicates it is part of the influenced group [64].

To determine the interactions among criteria, the average of the defuzzified values is computed. The criteria with values above the average are considered mutually influential. However, this method does not indicate the strength of relationships. Therefore, a threshold value is set by averaging the influence-relation map, and relationships below this threshold are disregarded. By comparing the maximum value in the defuzzified values matrix to the threshold, relationships are classified as weak, moderate, or strong, and ensure clarity in the influence-relation map [55].

### *3.5. Interpretive Structural Modeling (ISM) Analyses*

Interpretive Structural Modeling (ISM) is a multi-level modeling approach commonly employed to reveal the structural relationships among factors within complex systems, typically based on data collected from experts [56]. However, since the determination of these directional codes predominantly relies on expert judgments, it inherently carries the risk of subjectivity.

To overcome this limitation, the present study integrates the ISM method with the Total Relationship Matrix (T matrix) obtained from the Fuzzy DEMATEL technique, which objectively captures both the strength and direction of relationships among factors. Specifically, strong interactions exceeding the threshold value are directly identified through the directional information in the Fuzzy DEMATEL T matrix. This approach enables a systematic and quantitative modeling of both the intensity and structural orientation of interactions within the ISM [70].

Consequently, the integration of these two methodologies results in a more robust, consistent, and analytically sound influence model. Subsequently, the ISM model is constructed based on the directions, classifications, and hierarchical levels of the relationships among the examined factors [50,51]. In this study, the ISM analysis used the outputs from the initial Fuzzy DEMATEL phase and was carried out using the SmartISM 2.0 software.

## 4. Results

### *4.1. Determination Factors Based on the Fuzzy Delphi Method*

Prior to the fuzzy Delphi assessment, a preliminary list of potential factors affecting the shipping industry in response to carbon emission regulations was meticulously compiled. The initial list was derived from a comprehensive review of the existing literature. The focus was on the following areas: freight rates, logistics costs, ship operating expenses, environmental and sustainability issues, alternative fuel use, compliance with international and legal regulations, investment decisions and competitive strength of shipowners and operators, and port infrastructure. These areas are further delineated in Section 2. The systematic review of the extant literature identified the challenges, opportunities and impact areas that are most frequently cited. This preliminary list, which was exhaustive, was subsequently presented to an expert panel in the first phase of the Fuzzy Delphi method. The experts refined the list by eliminating unnecessary items, by suggesting additional relevant factors not addressed in the initial review, and by merging synonymous factors. This process ultimately created a comprehensive criteria list for fuzzy evaluation.

To determine the impact levels of the finalized criteria, a survey was developed using the linguistic variables presented in Table 2. As outlined in the first step of our methodology, the Fuzzy Delphi Method was applied to identify the factors affecting carbon emission practices in the maritime sector.

In determining the most influential factors, the importance ranking values ($S_j$) for each factor were calculated using Equation (3), while the expert agreement values ($EA_j$) were computed according to Equation (7). Factors with ($S_j$) values of 0.7 or higher were considered more influential and thus retained, whereas those below this threshold were excluded [56,59]. Expert group consensus was assessed based on the criterion that at least 75% of the experts agreed on each factor ($EA_j \geq 75\%$). Factors failing to meet this condition were eliminated.

Based on the survey results and consensus reached through the Fuzzy Delphi Method, the factors influencing carbon emission regulations in the maritime sector, along with their brief descriptions, are presented in Table 4.

**Table 4.** Final criteria selected by the fuzzy delphi method.

| Criteria No | Criteria Name | Brief Descriptions | Importance Indicator ($S_j$) | Consensus Indicator ($EA_j$) |
|---|---|---|---|---|
| C1 | Ship Operating Costs | Increase in fuel prices, operating profitability | 0.77 | 75% |
| C2 | Fuel Preferences and Alternative Fuel Usage | Preference for alternative fuels such as lng, hydrogen, and methanol | 0.84 | 88% |
| C3 | Port Infrastructure | Availability of low-carbon fuel supply | 0.82 | 88% |
| C4 | Investment Decisions of Shipowners and Charterers | Acquisition or commissioning of new vessels | 0.72 | 75% |
| C5 | Logistics Costs | Reflection of carbon tax on freight rates | 0.77 | 88% |
| C6 | Industry Competition | Competitiveness of international and national maritime companies | 0.71 | 75% |
| C7 | Environmental Protection and Sustainability | Reduction in emissions, green shipping policies, and ensuring supply sustainability | 0.82 | 88% |
| C8 | Adaptation to International and National Regulations | Adaptation to imo regulations and other carbon regulatory decisions | 0.77 | 88% |

### *4.2. Determining Influence-Effect Relationships Among Factors*

In this section, the most important factors identified through the Fuzzy Delphi method were extracted for the Fuzzy DEMATEL analysis, as presented in Table 4. To analyze the cause-effect relationships among these factors, a paired-matrix questionnaire was administered to experts. Expert opinions were collected as linguistic data and subsequently fuzzified. The averages of the resulting fuzzy values were calculated using Equations (A1) and (A2), leading to the formation of the "Average Direct Effect Matrix" ($\widetilde{Z}$) Thereafter, the ($\widetilde{Z}$) matrix was normalized using Equations (A3) and (A4), resulting in the "Normalized Direct Effect Matrix"($\widetilde{X}$) In the final stage, the obtained $\widetilde{X}$ matrix was processed by applying

Equations (A5)–(A10), producing the "Fuzzy Total Relationship Matrix" ($\widetilde{T}$). The detailed matrices ($\widetilde{Z}$, $\widetilde{X}$ and $\widetilde{T}$) are provided in Appendix B. Ultimately, the defuzzification of the $\widetilde{T}$ matrix was performed using the CFCS method as per Equations (A11)–(A16), and the resulting "Total Relationship Matrix (T)" is presented in Table 5. The data analysis was conducted using the Online Output MCDM Software.

**Table 5.** The total relation matrix shows the relationships between factors.

| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
|---|---|---|---|---|---|---|---|---|
| **C1** | 0.891 | 1.034 | 0.893 | 1.071 | 1.027 | 1.053 | 1.022 | 0.950 |
| **C2** | 1.061 | 1 | 0.964 | 1.144 | 1.089 | 1.117 | 1.110 | 1.026 |
| **C3** | 0.978 | 1.042 | 0.811 | 1.053 | 1.003 | 1.037 | 1.040 | 0.962 |
| **C4** | 1.020 | 1.085 | 0.925 | 1 | 1.054 | 1.096 | 1.074 | 0.993 |
| **C5** | 0.955 | 1.011 | 0.856 | 1.046 | 0.895 | 1.029 | 0.991 | 0.938 |
| **C6** | 1.030 | 1.083 | 0.938 | 1.119 | 1.059 | 0.985 | 1.072 | 1.004 |
| **C7** | 0.994 | 1.024 | 0.893 | 1.070 | 1.012 | 1.037 | 0.930 | 0.969 |
| **C8** | 1.050 | 1.110 | 0.953 | 1.140 | 1.078 | 1.105 | 1.106 | 0.924 |

Table 5 shows that all factors exert some degree of influence on one another. However, due to the limited interpretability and practical utility of the raw Impact-Relation Diagram, a threshold value was established, and only interactions exceeding this threshold were considered for further analysis. In this study, the threshold value of 1.016 was determined by calculating the average of all values within the defuzzified "Total Relationship Matrix (T matrix)".

The interactions between factors exceeding this threshold were identified by calculating the average of the defuzzified values. To prevent the Impact-Relation Map from becoming overly complex and visually dense, the strength of the interactions was categorized by dividing the range from the threshold (1.016) to the highest observed value (1.144) into three equal intervals. Accordingly, values between 1.016 and 1.058 represent weak interactions, those between 1.058 and 1.101 indicate moderate interactions, and those between 1.101 and 1.144 denote strong interactions.

In Table 6, the intensity levels of influence are visualized using color coding: red indicates strong influence, orange represents moderate influence, and green denotes weak influence. Accordingly, C8 exerts a strong influence on C2, C4, C6, and C7; C2 strongly influences C4, C6, and C7; and C6 has a strong influence on C4.

**Table 6.** Interaction intensity between factor pairs exceeding the threshold value.

| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
|---|---|---|---|---|---|---|---|---|
| **C1** | | 1.034 | | 1.071 | 1.027 | 1.053 | 1.022 | |
| **C2** | 1.061 | | | 1.144 | 1.089 | 1.117 | 1.110 | 1.026 |
| **C3** | | 1.042 | | 1.053 | | 1.037 | 1.040 | |
| **C4** | 1.020 | 1.085 | | | 1.054 | 1.096 | 1.074 | |
| **C5** | | | | 1.046 | | 1.029 | | |
| **C6** | 1.030 | 1.083 | | 1.119 | 1.059 | | 1.072 | |
| **C7** | | 1.024 | | 1.070 | | 1.037 | | |
| **C8** | 1.050 | 1.11 | | 1.14 | 1.078 | 1.105 | 1.106 | |

### *4.3. Creating the Influence-Dependence Map*

In the next step, the influence–relation map was constructed. As the initial phase of this process, the row sums (D) and column sums (R) were calculated using Equations (A17) and (A18). Based on these values, the corresponding D − R and D + R values were computed and presented in Table 7.

**Table 7.** D + R and D − R values.

| | R | D | D + R | D − R | |
|---|---|---|---|---|---|
| **C1** | 7.978 | 7.94 | 15.917 | −0.038 | Effect |
| **C2** | 8.391 | 8.51 | 16.901 | 0.12 | Cause |
| **C3** | 7.234 | 7.925 | 15.159 | 0.691 | Cause |
| **C4** | 8.643 | 8.248 | 16.891 | −0.395 | Effect |
| **C5** | 8.218 | 7.721 | 15.938 | −0.497 | Effect |
| **C6** | 8.458 | 8.291 | 16.749 | −0.167 | Effect |
| **C7** | 8.344 | 7.928 | 16.272 | −0.415 | Effect |
| **C8** | 7.766 | 8.467 | 16.233 | 0.702 | Cause |

The D−R value calculated for each criterion represents the vertical axis of the influence–relation map, indicating the causal role of the factor within the system. A positive D − R value implies that the factor belongs to the "driving group" (i.e., influencing other factors), while a negative value suggests that the factor is part of the "dependent group" (i.e., being influenced). The D + R values are plotted on the horizontal axis, reflecting the overall importance or prominence of the factor in the system. Based on the D − R and D + R values, the influence–relation map is constructed and presented in Figure 4.

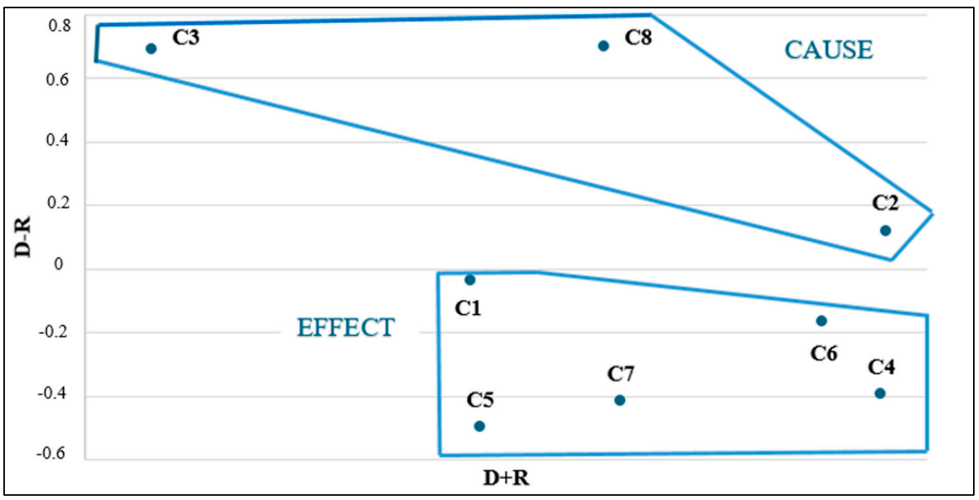



**Figure 4.** Influence–Dependence Map Generated via Fuzzy DEMATEL Analysis.

Based on the vertical vector (D − R) values, C8, C3, and C2 are identified as driving factors due to their high influencing strength, while C5, C7, C4, C6, and C1 are recognized as dependent factors according to their degree of being influenced.

### *4.4. Calculating Factors Weights*

The weights of the criteria were calculated using Equations (A19) and (A20). The resulting values of (D + R) and (D − R), along with the computed criterion weights, are presented in detail in Table 8 below.

The wi value is indicative of the overall prominence of a factor within the system by considering both its influence on other factors (influential power) and the influence of other factors on it (dependence). It can be posited that an elevated wi value indicates that the relevant factor plays a more significant role within the system. Conversely, the WI value signifies the normalized weight of each factor. The normalized WI value of each factor is obtained by dividing the WI value of each factor by the sum of all WI values. The purpose of normalizing the weights is to ensure that their total sum is exactly 1. This makes the relative importance of each factor clear and directly comparable, enabling factors to be ranked.

**Table 8.** Factor weights and ranking.

| | R | D | D + R | D − R | wi | WI |
|---|---|---|---|---|---|---|
| C2 | 8.391 | 8.51 | 16.901 | 0.12 | 16.90143 | 0.129901 |
| C4 | 8.643 | 8.248 | 16.891 | −0.395 | 16.89562 | 0.129857 |
| C6 | 8.458 | 8.291 | 16.749 | −0.167 | 16.74983 | 0.128736 |
| C7 | 8.344 | 7.928 | 16.272 | −0.415 | 16.27729 | 0.125104 |
| C8 | 7.766 | 8.467 | 16.233 | 0.702 | 16.24817 | 0.12488 |
| C5 | 8.218 | 7.721 | 15.938 | −0.497 | 15.94575 | 0.122556 |
| C1 | 7.978 | 7.94 | 15.917 | −0.038 | 15.91705 | 0.122335 |
| C3 | 7.234 | 7.925 | 15.159 | 0.691 | 15.17474 | 0.11663 |

As a result of the weighting analysis, the relative importance ranking of the factors was identified in the following order: C2, C4, C6, C7, C8, C5, C1, and C3.

### *4.5. Results of the Interpretive Structural Modeling (ISM) Analyses*

The Final Reachability Matrix (FRM), resulting from the determination of inter-factor transition relationships based on the matrix in Table 9, is presented in Table 10.

**Table 9.** Reachability matrix (RM).

| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | Driving Power |
|---|---|---|---|---|---|---|---|---|---|
| **C1** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 6 |
| **C2** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 7 |
| **C3** | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 5 |
| **C4** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 6 |
| **C5** | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 3 |
| **C6** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 6 |
| **C7** | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 4 |
| **C8** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 7 |
| **Dependence Power** | 5 | 7 | 1 | 8 | 6 | 8 | 7 | 2 | |

**Table 10.** Final reachability matrix (FRM).

| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | Driving Power |
|---|---|---|---|---|---|---|---|---|---|
| **C1** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1* | 7 |
| **C2** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 7 |
| **C3** | 1* | 1 | 1 | 1 | 1* | 1 | 1 | 1* | 8 |
| **C4** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1* | 7 |
| **C5** | 1* | 1* | 0 | 1 | 1 | 1 | 1* | 1* | 7 |
| **C6** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1* | 7 |
| **C7** | 1* | 1 | 0 | 1 | 1* | 1 | 1 | 1* | 7 |
| **C8** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 7 |
| **Dependence Power** | 8 | 8 | 1 | 8 | 8 | 8 | 8 | 8 | |

The level determination process based on the FRM, which includes the transition relationships presented in Table 10, is illustrated in the Level Partitioning (LP) shown in Table 11.

Following the determination of the criteria levels, a multi-layered hierarchical structural model was developed. The modeling of the results obtained through the Fuzzy DEMATEL method using ISM analysis is presented in Figure 5.

**Table 11.** Level partitioning (LP).

| Elements (Mi) | Reachability Set R(Mi) | Antecedent Set A(Ni) | Intersection Set R(Mi)∩A(Ni) | Level |
|---|---|---|---|---|
| 1 | 1, 2, 4, 5, 6, 7, 8, | 1, 2, 3, 4, 5, 6, 7, 8, | 1, 2, 4, 5, 6, 7, 8, | 1 |
| 2 | 1, 2, 4, 5, 6, 7, 8, | 1, 2, 3, 4, 5, 6, 7, 8, | 1, 2, 4, 5, 6, 7, 8, | 1 |
| 3 | 1, 2, 3, 4, 5, 6, 7, 8 | 3 | 3 | 2 |
| 4 | 1, 2, 4, 5, 6, 7, 8, | 1, 2, 3, 4, 5, 6, 7, 8, | 1, 2, 4, 5, 6, 7, 8, | 1 |
| 5 | 1, 2, 4, 5, 6, 7, 8, | 1, 2, 3, 4, 5, 6, 7, 8, | 1, 2, 4, 5, 6, 7, 8, | 1 |
| 6 | 1, 2, 4, 5, 6, 7, 8, | 1, 2, 3, 4, 5, 6, 7, 8, | 1, 2, 4, 5, 6, 7, 8, | 1 |
| 7 | 1, 2, 4, 5, 6, 7, 8, | 1, 2, 3, 4, 5, 6, 7, 8, | 1, 2, 4, 5, 6, 7, 8, | 1 |
| 8 | 1, 2, 4, 5, 6, 7, 8, | 1, 2, 3, 4, 5, 6, 7, 8, | 1, 2, 4, 5, 6, 7, 8, | 1 |

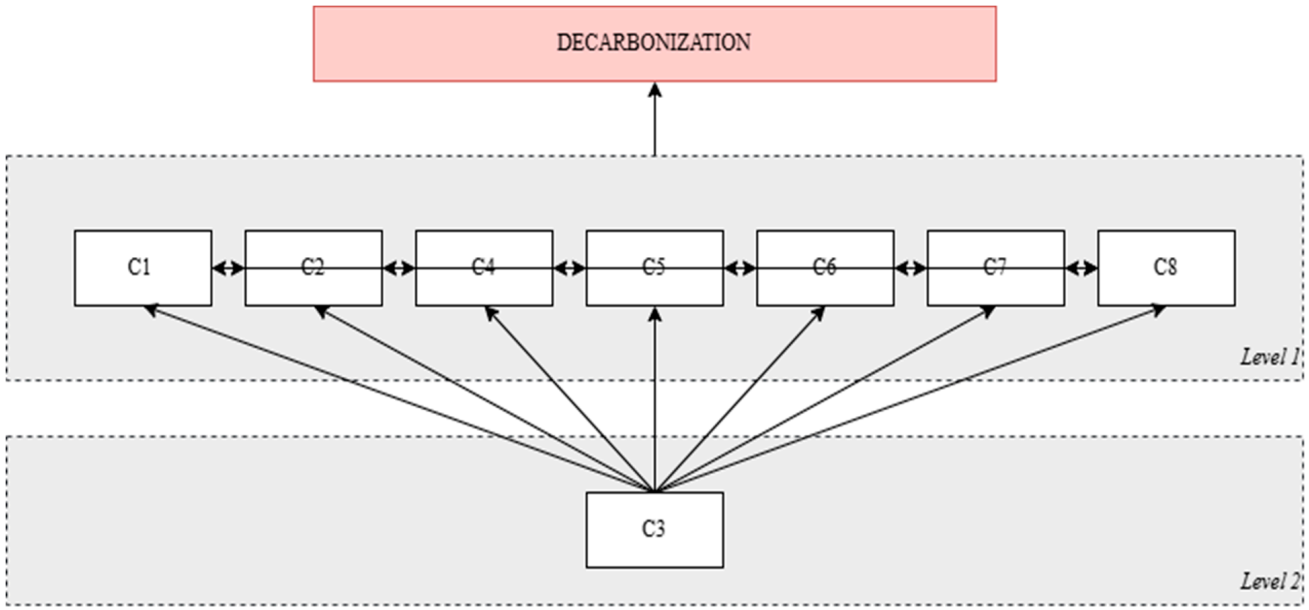



**Figure 5.** Carbon emission regulations impact model. Level 1: Represents the lowest layer in the ISM model. Factors at this level are influenced by other elements but do not directly influence other factors. They are generally result-oriented towards outcomes and in the process. Level 2: Factors at this level, directly affect Level 1 and are less affected by higher levels, which are above Level 1. They are positioned as both influencing and influenced intermediate factors.

The ISM analysis reveals that the majority of the criteria are positioned at the same level based on the responses provided by experts, and the DEMATEL outcome, with only the C3 factor occupying the second level. This finding suggests that the causal relationships between criteria do not demonstrate a pronounced hierarchical structure, and that the factors interact at analogous levels. The differentiation of the C3 factor at another level reveals that this criterion has a more distinct and powerful influence compared to the others, and that it is a pivotal factor that directs the system. It is evident from the extant literature that the outputs of ISM are observed as single-layer or limited-layer structures. This phenomenon is considered to be a direct reflection of the relationship matrix derived from expert evaluations.

## 5. Discussion

The issue of carbon emission regulations holds critical importance in the maritime industry and is a continuously evolving domain. These regulations are closely aligned with environmental objectives. Accordingly, the present study examines the interactions among the criteria determined through the Fuzzy Delphi method within the context of the influence of carbon emission regulations. To evaluate the effectiveness of these regulations, the

intensity and significance levels of their impacts were analyzed using the Fuzzy DEMATEL method. Subsequently, the DEMATEL outputs were structurally modeled through the ISM.

The findings of the study indicate that C8—"Adaptation to International and National Regulations", C3—"Port Infrastructure" and C2—"Fuel Preferences and Alternative Fuel Usage" function as driving factors influencing other variables, whereas C5—"Logistics Costs", C7—"Environmental Protection and Sustainability", C4—"Investment Decisions of Shipowners and Charterers," C1—"Ship Operating Costs," and C6—"Industry Competition" are identified as dependent variables (see Figure 4).

Furthermore, the C8 "Adaptation to International and National Regulations" factor exerts a strong influence on C2 "Fuel Preferences and Alternative Fuel Usage", C4 "Investment Decisions of Shipowners and Charterers", C6 "Industry Competition" and C7 "Environmental Protection and Sustainability." Similarly, the C2 factor has a significant impact on C4, C6, and C7, while the C6 factor demonstrates a substantial effect on C4. These results reveal that the aforementioned factors directly induce sequential effects within the system (see Table 6).

Within the analyzed system, C8 "Adaptation to International and National Regulations" and C3 "Port Infrastructure" emerge as the most dominant driving factors (see Figure 4) and serve as the primary guiding elements in the existing interaction network. The strong influence of C8 underscores, the critical importance of designing both current and future international and regional carbon emission regulations with predictability and incentive mechanisms, as also noted in Gössling et al. [34]. Moreover, the ability of maritime enterprises to rapidly adapt to these regulatory frameworks confers a distinct competitive advantage within the sector. While large-scale companies and emerging economies possess the potential to comply with such regulations, small-scale maritime operators face the risk of marginalization and exclusion from competition.

The high causal power attributed to the C3 "Port Infrastructure" factor underscores the necessity of accelerating infrastructure transformation to facilitate the adoption of alternative fuels, guide the investment decisions of shipowners and charterers, and achieve broader environmental sustainability objectives. The compatibility and rapid adaptability of port infrastructure play a critical role in enabling fuel transitions and ensuring the sustainability of the maritime supply chain. This argument is also supported by the empirical evidence presented in Jia et al. [41] and Wan et al. [6].

Conversely, the factors C5 "Logistics Costs" C7 "Environmental Protection and Sustainability" and C4 "Investment Decisions of Shipowners and Charterers" are identified as the most affected variables within the system (see Figure 4). The C5 factor, in particular, is directly sensitive to regulatory policies such as market-based carbon taxation and fluctuations in fuel prices. This perspective is corroborated by findings reported in Wu et al. [14] and Rojon et al. [4], which document the potential of carbon taxes to increase freight rates.

The C7 "Environmental Protection and Sustainability" factor represents the output-oriented dimension of the system, which constitutes its ultimate objective and is therefore directly influenced by the primary driving variables. Accordingly, the alignment of strategic decisions with environmental goals is imperative for advancing the decarbonization process. Achieving success in environmental sustainability requires firm and holistic measures targeting C2, C8, and C3. Regulatory frameworks such as EEXI, CII, and ETS are specifically designed to accelerate the transition toward green shipping by reducing emissions, a view also supported by Oh et al. [5] and Kotzampasakis [24].

Finally, the C4 "Investment Decisions of Shipowners and Charterers" factor is predominantly shaped by influential variables namely C2 and C8, exhibiting substantial sensitivity to their effects (see Table 6). Shipowners and operators are compelled to align new building projects, retrofitting activities, and commercial investments with existing regulatory

requirements such as CII, ETS, and GFI. These findings are consistent with the empirical evidence reported in Trosvik and Brynolf [37] and Flodén et al. [39].

Another fundamental objective of this study is to determine the relative importance of the factors influencing carbon emission regulations in the maritime industry. According to the weight analysis, C2 "Fuel Preferences and Alternative Fuel Usage" is identified as the most significant factor (see Table 8). This variable exhibits the highest level of interaction within the system and exerts a strong influence on C4, C6, and C7. The two-tier (Tier-I, Tier-II) calculation mechanisms based on the WtW principle implemented in the EU's FuelEU and IMO's GFI regulations have increased the relevance of alternative fuels such as LNG and ammonia. Establishing a time frame for selecting and adopting fuel types compatible with the 2050 emission reduction targets is of critical importance. The use of low-carbon fuels provides direct environmental benefits and has become mandatory under recent regulations. Furthermore, alternative fuel incentives constitute a decisive factor that strongly shapes the competitive structure of the sector. These findings are supported by Shi et al. [3], He et al. [13], and Hellström et al. [25].

The second, third, and fourth most important factors are identified as C4 "Investment Decisions of Shipowners and Charterers" C6 "Industry Competition," and C7 "Environmental Protection and Sustainability," respectively (Table 8). As previously emphasized, these factors are largely influenced by the primary variable C2. The C4 factor is particularly sensitive to market-based regulations; maritime enterprises that invest in new technologies gain a competitive advantage within the context of C6. Consequently, competition emerges at the local level between firms that comply with stringent carbon regulations and those that do not. As demonstrated in Wang and Zhu [40], such competitive behavior encourages environmental objectives to become strategic priorities for shipowners and maritime companies.

The ISM results obtained following the Fuzzy DEMATEL analysis indicate that C3 "Port Infrastructure" plays a fundamental role within the input layer (Level 2), whereas the remaining variables (C1, C2, C4, C5, C6, C7, and C8) are positioned within the output layer (Level 1) as outcome or intermediary variables. Located at the lower tier of the model, C3 functions as the foundational variable affecting all higher-level interactive factors. Since fuel transition and bunkering for low-carbon vessels require long-term efforts to ensure port infrastructure compatibility, C3 serves as a prioritizing, determinative, and catalytic factor within the system. The hierarchical structural model developed through ISM (Figure 5) reveals that port infrastructure functions as a critical starting point capable of triggering all other factors.

The core findings of this study are grounded in a MCDM framework derived from expert opinions and are supported by similar studies in the literature. Nevertheless, it is important that these findings be further validated through secondary quantitative data using a triangulation approach. The identification of "Port Infrastructure" (C3) as the primary causal factor (ISM Level 2, Figure 5) and "Fuel Preferences and Alternative Fuel Usage" (C2) as the most critical factor in terms of overall importance (Table 8) aligns strongly with current industry trends and regulatory developments.

The EU's FuelEU Maritime initiative and the IMO's recently adopted NZF regulation mandate the use of low-carbon fuels and aim to monitor and reduce emissions through mechanisms such as GHG Fuel Intensity (GFI) calculations [71,72]. To ensure effective compliance with these regulations, port infrastructure must be fully compatible with the bunkering, storage, and supply of alternative fuels such as LNG, ammonia, and methanol. This further reinforces the critical role of C3 in the decarbonization process. The Port of Rotterdam is widely recognized as an innovation hub in sustainable maritime logistics and demonstrates a pioneering approach in this regard. Its initiatives include shore-

side electrification facilities, LNG and biofuel bunkering infrastructure, digital logistics platforms, and carbon capture and storage (CCS) projects. These initiatives illustrate that comprehensive planning and the adoption of advanced technologies can directly contribute to infrastructure development [73–75].

Furthermore, the finding that C2 is the most critical factor is quantitatively supported by the greenhouse gas reduction targets set by the IMO and the EU, which necessitate a fundamental shift away from fossil fuels. Empirical studies conducted by organizations such as SEA-LNG and SGMF demonstrate tangible benefits, including a 14–16% reduction in the carbon footprint of LNG-powered vessels. These studies also provide concrete operational data that validate the importance of adopting alternative fuels. Moreover, the allocation savings granted to LNG-fueled vessels under the EU ETS constitute a direct economic incentive that reflects the significance of fuel choice.

Although comprehensive and detailed operational data for the entire Turkish maritime sector remain beyond the scope of this study, findings derived from expert judgments supported by quantitative research and regulatory developments in the existing literature enhance the overall credibility and practical applicability of the model.

## 6. Conclusions

This study adopts a methodological approach that integrates Fuzzy Delphi, Fuzzy DEMATEL, and ISM techniques to analyze the impacts of carbon emission regulations on the maritime sector from a multi-criteria and influence-based perspective. The research aims to address the lack of systematic, multi-layered, and integrated analyses in this field, while simultaneously presenting an innovative model for sectoral decision-makers.

In the first phase of the study, eight main criteria determining the impact of carbon emission regulations on the sector were identified based on expert input collected through the Fuzzy Delphi method. Among these criteria, “Fuel Preferences and Alternative Fuel Usage” (C2) was determined to be the most significant factor.

The results of the Fuzzy DEMATEL analysis revealed that “Adaptation to International and National Regulations” (C8) and “Port Infrastructure” (C3) are the most influential driving factors within the system, acting as directional and triggering variables over all other criteria.

Furthermore, the hierarchical structural model developed through the ISM approach positioned “Port Infrastructure” (C3) within the input layer of the system, reinforcing the conclusion that infrastructure constitutes the fundamental determinant of the entire structure. In addition, factors “Logistics Costs” (C5), “Environmental Protection and Sustainability” (C7), and “Investment Decisions of Shipowners and Investors” (C4) were located in the output layer, indicating that they are shaped by the influence of other variables and are the most affected components of the regulatory process.

Moreover, the developed influence-dependence relationship map quantitatively illustrates the dynamic interactions among sectoral factors and holds strong potential to serve as a high-resolution decision-support tool for policymakers. The proposed sectoral structural model provides guidance for identifying strategic planning priorities.

### *6.1. Implications and Recommendations for Low-Carbon Maritime Transition*

For Policymakers:

- A clear hierarchy of investment priorities should be established, with particular emphasis on the development of alternative fuel bunkering facilities (e.g., LNG, methanol, ammonia) and shore-side electricity connections.

- Targeted incentives should be introduced to support infrastructure modernization and the construction of alternative-fuel vessels, while encouraging public–private partnerships.
- Emission policies should be published in a phased and transparent manner to facilitate strategic planning, reduce financial risks, and promote a feasible and effective transition across the sector.
- Mechanisms should be designed to facilitate small- and medium-sized enterprises' compliance with national and international regulations. Technical guidance or financial assistance should be provided for the retrofitting of existing vessels to safeguard their competitive advantages.

For Maritime Companies:

- Proactive compliance strategies for forthcoming emission regulations should be developed.
- Fuel selection, new buildings, and retrofit projects should be aligned with well-to-wake (WtW) emission calculation methodologies to establish coherent decarbonization targets.
- Collaboration with port authorities and policymakers should be pursued to identify and implement necessary infrastructure upgrades.
- Environmental protection and sustainability should be adopted as strategic priorities. Voyage planning and speed–route optimization should be utilized to minimize both operational costs and regulatory burdens.

Taken collectively, these recommendations provide a pathway for a more structured, balanced and inclusive transition of the maritime industry towards a low-carbon future. The key scientific contribution of this study to existing literature lies in its adoption of a holistic approach to carbon emission regulation. While most prior research has remained one-dimensional or limited to economic implications, this study presents a multi-criteria framework that simultaneously evaluates economic, environmental, operational and structural factors.

### *6.2. Contribution to Literature and Industry*

This study provides a comprehensive analytical framework capable of supporting multidimensional decision-making processes for shipowners, vessel operators, port authorities, and policymakers within the maritime sector. The findings obtained through the integrated application of Fuzzy Delphi, Fuzzy DEMATEL, and ISM methodologies enable sector stakeholders to clearly identify which impact domains carbon emission regulations predominantly influence, as well as to distinguish between factors positioned as causal (driving) and those as effect (dependent) variables within the system.

Moreover, the study reveals not only the economic and cost-related impacts of these regulations but also their multifaceted effects on environmental sustainability, operational transformation, and sectoral competitiveness through complex interaction networks. Considering that most existing literature adopts unidimensional approaches to analyzing carbon emission regulations, this research addresses a significant gap by employing MCDM methods and causality analysis enhanced by fuzzy logic. Particularly, the integrated model developed through the combination of Delphi, DEMATEL, and ISM methods offers a unique and methodologically robust contribution to both practical sectoral policy design and academic literature.

### *6.3. Limitations and Future Research*

In the course of the study, the research team sought the input of 12 experts during the data collection phase. While this number of experts is considered to be methodologically appropriate for the MCDM techniques employed (particularly Fuzzy Delphi and DEMATEL), it remains modest in terms of quantitative research frameworks and could be

expanded to include a broader expert network. In future studies, obtaining more comprehensive results may be facilitated by the incorporation of experts from diverse stakeholder groups, including port authorities, legal regulators, and ship operating companies. It is recommended that future studies include impact analyses broken down by ship type (e.g., tankers, bulk carriers, container ships) and provide more specific data on how each ship segment is affected by carbon regulations.

It is recommended that future research endeavors incorporate a more diverse set of examples, by including cases from various countries and insight from other relevant stakeholders, such as port authorities, regulatory bodies, and ship classification organizations. This approach is expected to yield more comprehensive results. Furthermore, the application of segmented impact analyses, long-term studies, and hybrid models developed through the application of various MCDM methods, all categorized by ship type, has the potential to further enrich research in this field.

Future research could achieve more comprehensive results by incorporating examples from different countries and including other stakeholder groups such as port authorities, regulators, and ship classification societies. Additionally, impact analyses segmented by vessel types, longitudinal studies, and hybrid models developed through the application of various MCDM methods may further enrich the research in this field.

**Author Contributions:** Conceptualization, O.H.A. and A.U.Ü.; methodology, O.H.A. and O.T.; software, O.T.; validation, O.H.A., O.T., A.U.Ü. and G.K.Ö.; formal analysis, O.T.; investigation, O.H.A.; resources, O.T. and A.U.Ü.; data curation, O.H.A.; writing—original draft preparation, O.H.A. and O.T.; writing—review and editing, O.H.A., A.U.Ü. and G.K.Ö.; visualization, A.U.Ü.; supervision, O.H.A. and A.U.Ü.; project administration, O.H.A.; All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** The survey conducted in this study was approved by the Kocaeli University Committee with protocol number 2025/01 on 17 January 2025 (Number: 20.01.2025-E.717243).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Data are contained within the article.

**Acknowledgments:** The authors have reviewed and edited the output and take full responsibility for the content of this publication.

**Conflicts of Interest:** Authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| IMO | International Maritime Organization |
| EU | European Union |
| ISM | Interpretive Structural Modeling |
| EEDI | Energy Efficiency Design Index |
| EEXI | Energy Efficiency Existing Ship Index |
| CII | Carbon Intensity Indicator |
| ETS | Emissions Trading System |
| EEA | European Economic Area |
| WtW | Well-to-Wake |
| EU MRV | EU Monitoring, Reporting and Verification |
| NZF | Net-Zero Framework |
| MEPC | Marine Environment Protection Committee |

| | |
|---|---|
| GFI | Greenhouse Gas Fuel Intensity |
| NSR | Northern Sea Route |
| SCR | Suez Canal Route |
| LNG | Liquefied Natural Gas |
| EU ETS | EU Emissions Trading System |
| JIT | Just-In-Time |
| MCDM | Multi-Criteria Decision-Making |
| AHP | Analytic Hierarchy Process |
| TOPSIS | Technique for Order Preference by Similarity to Ideal Solution |
| VIKOR | VlseKriterijumska Optimizacija I Kompromisno Resenje |
| ELECTRE | Elimination and Choice Expressing Reality |
| GRA | Grey Relational Analysis |
| BWM | Best-Worst Method |
| DPA | Designated Person Ashore |
| TFNs | Triangular Fuzzy Numbers |
| RM | Reachability Matrix |
| FRM | Final Reachability Matrix |
| LP | Level Partitioning |
| CCS | Carbon Capture and Storage |

## Appendix A. Fuzzy DEMATEL Mathematics (Equations)

$$\widetilde{Z}^k = \left[\widetilde{z}_{ij}^k\right]_{nxn} \widetilde{Z}_{ij}^k = \left(z_{ijl}^k, z_{ijm}^k, z_{iju}^k\right) \tag{A1}$$

$$\widetilde{z}_{ij} = \left(z_{ijl}, z_{ijm}, z_{iju}\right) = \frac{1}{k}\sum_{k=1}^{k}\widetilde{z}_{ij}^k = \left(\frac{1}{k}\sum_{k=1}^{k} z_{ijl}^k, \frac{1}{k}\sum_{k=1}^{k} z_{ijm}^k, \frac{1}{k}\sum_{k=1}^{k} z_{iju}^k,\right)$$

$$\widetilde{Z} = \begin{bmatrix} 0 & \widetilde{z}_{12} & \dots & \widetilde{z}_{1n} \\ \widetilde{z}_{21} & 0 & \ddots & \widetilde{z}_{2n} \\ \vdots & \ddots & 0 & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ \widetilde{z}_{n1} & \widetilde{z}_{n2} & \dots & 0 \end{bmatrix} \tag{A2}$$

$$\widetilde{X} = \begin{bmatrix} 0 & \widetilde{x}_{12} & \dots & \widetilde{x}_{1n} \\ \widetilde{x}_{21} & 0 & \ddots & \widetilde{x}_{2n} \\ \vdots & \ddots & 0 & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ \widetilde{x}_{n1} & \widetilde{x}_{n2} & \dots & 0 \end{bmatrix} \quad \widetilde{x}_{ij} = \frac{\widetilde{z}_{ij}}{r} = \left(\frac{z_{ijl}}{r}, \frac{z_{ijm}}{r}, \frac{z_{iju}}{r}\right) \tag{A3}$$

$$r = \max_{1 \le i \le n}\left(\sum_{j=1}^{n} z_{iju}\right)$$

$$\widetilde{X}_l = \begin{bmatrix} 0 & l_{12} & \dots & l_{1n} \\ l_{21} & 0 & \ddots & l_{2n} \\ \vdots & \ddots & 0 & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ l_{n1} & l_{n2} & \dots & 0 \end{bmatrix}, \widetilde{X}_m = \begin{bmatrix} 0 & m_{12} & \dots & m_{1n} \\ m_{21} & 0 & \ddots & m_{2n} \\ \vdots & \ddots & 0 & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ m_{n1} & m_{n2} & \dots & 0 \end{bmatrix}, \widetilde{X}_u = \begin{bmatrix} 0 & u_{12} & \dots & u_{1n} \\ u_{21} & 0 & \ddots & u_{2n} \\ \vdots & \ddots & 0 & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ u_{n1} & u_{n2} & \dots & 0 \end{bmatrix} \tag{A4}$$

$$\widetilde{T} = \lim_{h \to \infty}\left(\widetilde{X}^1 + \widetilde{X}^2 + \ldots + \widetilde{X}^h\right) = \widetilde{X}\left(I - \widetilde{X}\right)^{-1} \tag{A5}$$

$$\widetilde{T} = \begin{bmatrix} 0 & \widetilde{t}_{12} & \dots & \widetilde{t}_{1n} \\ \widetilde{t}_{21} & 0 & \ddots & \widetilde{t}_{2n} \\ \vdots & \ddots & 0 & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ \widetilde{t}_{n1} & \widetilde{t}_{n2} & \dots & 0 \end{bmatrix} \quad \widetilde{t}_{ij} = \left(\acute{l}_{ij}, \acute{m}_{ij}, \acute{u}_{ij},\right) \tag{A6}$$

$$\widetilde{T}_l = \widetilde{X}_l \left(I - \widetilde{X}_l\right)^{-1} \tag{A7}$$

$$\widetilde{T}_m = \widetilde{X}_m \left(I - \widetilde{X}_m\right)^{-1} \tag{A8}$$

$$\widetilde{T}_u = \widetilde{X}_u \left(I - \widetilde{X}_u\right)^{-1} \tag{A9}$$

$$\widetilde{T} = \left(l_{ij}, m_{ij},\ u_{ij}\right) \stackrel{\text{def}}{=} x_{net} \tag{A10}$$

$$L = min\left(l_{ij}\right), R = max\left(u_{ij}\right), \Delta = R - L; \tag{A11}$$

$$x_l = l_{ij} - L/\Delta\ x_m = m_{ij} - L/\Delta\ x_u = u_{ij} - L/\Delta; \tag{A12}$$

$$x_{left} = x_m/(1 + x_m - x_l),\ \ x_{right} = x_u/(1 + x_u - x_{lm}); \tag{A13}$$

$$x = \left[x_{sol}\left(1 - x_{left}\right) + {x_{right}}^2\right] / \left[1 - x_{left} + x_{right}\right] \tag{A14}$$

$$x_{net} = L + \Delta x \tag{A15}$$

$$x_{net} = L + \Delta \frac{\left(m_{ij} - L\right)\left(\Delta + u_{ij} - m_{ij}\right)^2\left(R - l_{ij}\right) + \left(u_{ij} - L\right)^2\left(\Delta + m_{ij} - l_{ij}\right)^2}{\left(\Delta + m_{ij} - l_{ij}\right)\left(\Delta + u_{ij} - m_{ij}\right)^2\left(R - l_{ij}\right) + \left(u_{ij} - L\right)\left(\Delta + m_{ij} - l_{ij}\right)^2\left(\Delta + u_{ij} - m_{ij}\right)} \tag{A16}$$

$$R = [r_i]_{nx1}\ C = \left[c_j\right]_{1xn}\ R = [r_i]_{nx1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{nx1} \tag{A17}$$

$$C = \left[c_j\right]_{1xn} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1xn} \tag{A18}$$

$$w_i = \sqrt{(R + C)^2 + (R - C)^2} \tag{A19}$$

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{A20}$$

## Appendix B. Matrix Values

**Table A1.** Step-4: The Average Direct Effects Matrix.

| | **C1** | **C2** | **C3** | **C4** | **C5** | **C6** | **C7** | **C8** |
|---|---|---|---|---|---|---|---|---|
| C1 | (0.000, 0.000, 0.000) | (0.583, 0.833, 0.917) | (0.417, 0.667, 0.833) | (0.667, 0.917, 1.000) | (0.667, 0.917, 1.000) | (0.667, 0.917, 1.000) | (0.500, 0.750, 0.917) | (0.417, 0.667, 0.833) |
| C2 | (0.667, 0.917, 1.000) | (0.000, 0.000, 0.000) | (0.583, 0.833, 0.917) | (0.750, 1.000, 1.000) | (0.667, 0.917, 1.000) | (0.667, 0.917, 1.000) | (0.750, 1.000, 1.000) | (0.583, 0.833, 0.917) |
| C3 | (0.417, 0.667, 0.917) | (0.667, 0.917, 1.000) | (0.000, 0.000, 0.000) | (0.500, 0.750, 0.917) | (0.417, 0.667, 0.917) | (0.500, 0.750, 1.000) | (0.667, 0.917, 1.000) | (0.500, 0.750, 1.000) |
| C4 | (0.500, 0.750, 1.000) | (0.750, 1.000, 1.000) | (0.417, 0.667, 0.917) | (0.000, 0.000, 0.000) | (0.583, 0.833, 1.000) | (0.750, 1.000, 1.000) | (0.667, 0.917, 1.000) | (0.500, 0.750, 0.917) |
| C5 | (0.417, 0.667, 0.917) | (0.583, 0.833, 1.000) | (0.250, 0.500, 0.750) | (0.667, 0.917, 1.000) | (0.000, 0.000, 0.000) | (0.667, 0.917, 1.000) | (0.417, 0.667, 0.917) | (0.500, 0.750, 0.917) |

**Table A1.** *Cont.*

| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
|---|---|---|---|---|---|---|---|---|
| C6 | (0.583, 0.833, 0.917) | (0.667, 0.917, 1.000) | (0.500, 0.750, 1.000) | (0.750, 1.000, 1.000) | (0.583, 0.833, 1.000) | (0.000, 0.000, 0.000) | (0.583, 0.833, 1.000) | (0.583, 0.833, 0.917) |
| C7 | (0.583, 0.833, 1.000) | (0.500, 0.750, 0.833) | (0.417, 0.667, 0.833) | (0.667, 0.917, 1.000) | (0.500, 0.750, 1.000) | (0.500, 0.750, 1.000) | (0.000, 0.000, 0.000) | (0.583, 0.833, 1.000) |
| C8 | (0.583, 0.833, 1.000) | (0.750, 1.000, 1.000) | (0.500, 0.750, 0.917) | (0.750, 1.000, 1.000) | (0.583, 0.833, 1.000) | (0.583, 0.833, 1.000) | (0.750, 1.000, 1.000) | (0.000, 0.000, 0.000) |

**Table A2.** Step 5: The normalized fuzzy direct-relation matrix.

| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
|---|---|---|---|---|---|---|---|---|
| C1 | (0.000, 0.000, 0.000) | (0.083, 0.119, 0.131) | (0.060, 0.095, 0.119) | (0.095, 0.131, 0.143) | (0.095, 0.131, 0.143) | (0.095, 0.131, 0.143) | (0.071, 0.107, 0.131) | (0.060, 0.095, 0.119) |
| C2 | (0.095, 0.131, 0.143) | (0.000, 0.000, 0.000) | (0.083, 0.119, 0.131) | (0.107, 0.143, 0.143) | (0.095, 0.131, 0.143) | (0.095, 0.131, 0.143) | (0.107, 0.143, 0.143) | (0.083, 0.119, 0.131) |
| C3 | (0.060, 0.095, 0.131) | (0.095, 0.131, 0.143) | (0.000, 0.000, 0.000) | (0.071, 0.107, 0.131) | (0.060, 0.095, 0.131) | (0.071, 0.107, 0.143) | (0.095, 0.131, 0.143) | (0.071, 0.107, 0.143) |
| C4 | (0.071, 0.107, 0.143) | (0.107, 0.143, 0.143) | (0.060, 0.095, 0.131) | (0.000, 0.000, 0.000) | (0.083, 0.119, 0.143) | (0.107, 0.143, 0.143) | (0.095, 0.131, 0.143) | (0.071, 0.107, 0.131) |
| C5 | (0.060, 0.095, 0.131) | (0.083, 0.119, 0.143) | (0.036, 0.071, 0.107) | (0.095, 0.131, 0.143) | (0.000, 0.000, 0.000) | (0.095, 0.131, 0.143) | (0.060, 0.095, 0.131) | (0.071, 0.107, 0.131) |
| C6 | (0.083, 0.119, 0.131) | (0.095, 0.131, 0.143) | (0.071, 0.107, 0.143) | (0.107, 0.143, 0.143) | (0.083, 0.119, 0.143) | (0.000, 0.000, 0.000) | (0.083, 0.119, 0.143) | (0.083, 0.119, 0.131) |
| C7 | (0.083, 0.119, 0.143) | (0.071, 0.107, 0.119) | (0.060, 0.095, 0.119) | (0.095, 0.131, 0.143) | (0.071, 0.107, 0.143) | (0.071, 0.107, 0.143) | (0.000, 0.000, 0.000) | (0.083, 0.119, 0.143) |
| C8 | (0.083, 0.119, 0.143) | (0.107, 0.143, 0.143) | (0.071, 0.107, 0.131) | (0.107, 0.143, 0.143) | (0.083, 0.119, 0.143) | (0.083, 0.119, 0.143) | (0.107, 0.143, 0.143) | (0.000, 0.000, 0.000) |

**Table A3.** Step 6: The fuzzy total-relation matrix.

| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
|---|---|---|---|---|---|---|---|---|
| C1 | (0.096, 0.484, 2.912) | (0.189, 0.647, 3.026) | (0.135, 0.517, 2.794) | (0.206, 0.678, 3.102) | (0.189, 0.620, 3.102) | (0.197, 0.647, 3.131) | (0.175, 0.625, 3.058) | (0.150, 0.564, 2.921) |
| C2 | (0.199, 0.657, 3.168) | (0.132, 0.604, 3.042) | (0.170, 0.586, 2.925) | (0.236, 0.753, 3.236) | (0.206, 0.678, 3.236) | (0.215, 0.708, 3.266) | (0.224, 0.715, 3.200) | (0.187, 0.639, 3.057) |
| C3 | (0.147, 0.554, 3.129) | (0.193, 0.636, 3.137) | (0.075, 0.414, 2.782) | (0.179, 0.638, 3.196) | (0.152, 0.572, 3.196) | (0.169, 0.607, 3.235) | (0.191, 0.625, 3.170) | (0.155, 0.556, 3.037) |
| C4 | (0.169, 0.602, 3.168) | (0.216, 0.689, 3.167) | (0.141, 0.536, 2.925) | (0.127, 0.587, 3.111) | (0.185, 0.632, 3.236) | (0.214, 0.678, 3.266) | (0.203, 0.667, 3.200) | (0.167, 0.594, 3.057) |
| C5 | (0.144, 0.542, 3.030) | (0.179, 0.614, 3.038) | (0.108, 0.471, 2.787) | (0.196, 0.644, 3.104) | (0.093, 0.474, 2.979) | (0.187, 0.614, 3.133) | (0.155, 0.583, 3.060) | (0.152, 0.545, 2.932) |
| C6 | (0.180, 0.617, 3.160) | (0.209, 0.686, 3.168) | (0.152, 0.550, 2.935) | (0.226, 0.718, 3.237) | (0.187, 0.638, 3.237) | (0.119, 0.559, 3.142) | (0.195, 0.664, 3.201) | (0.178, 0.609, 3.058) |
| C7 | (0.169, 0.579, 3.103) | (0.175, 0.624, 3.082) | (0.133, 0.506, 2.855) | (0.202, 0.664, 3.169) | (0.165, 0.588, 3.169) | (0.172, 0.614, 3.198) | (0.105, 0.515, 3.008) | (0.167, 0.571, 3.003) |
| C8 | (0.186, 0.636, 3.202) | (0.225, 0.717, 3.200) | (0.157, 0.567, 2.956) | (0.233, 0.740, 3.270) | (0.193, 0.658, 3.270) | (0.202, 0.686, 3.300) | (0.221, 0.704, 3.233) | (0.107, 0.522, 2.973) |

## References

1. Arıcan, O.H. Selecting the most economical ship type for the marine business investor: A hybrid approach with PSI-PIPRECIA-COCOSO Methods. *Int. J. Contemp. Econ. Adm. Sci.* **2024**, *14*, 833–853. [CrossRef]
2. Lugovskyy, V.; Skiba, A.; Terner, D. Unintended consequences of environmental regulation of maritime shipping: Carbon leakage to air shipping. *J. Int. Econ.* **2025**, *155*, 104081. [CrossRef]
3. Shi, J.; Zhu, Y.; Feng, Y.; Yang, J.; Xia, C. A prompt decarbonization pathway for shipping: Green hydrogen, ammonia, and methanol production and utilization in marine engines. *Atmosphere* **2023**, *14*, 584. [CrossRef]

4. Rojon, I.; Lazarou, N.J.; Rehmatulla, N.; Smith, T. The impacts of carbon pricing on maritime transport costs and their implications for developing economies. *Mar. Policy* **2021**, *132*, 104653. [CrossRef]
5. Oh, J.; Kim, D.; Roussanaly, S.; Lim, Y. Greenhouse gas emissions of shipping with onboard carbon capture under the FuelEU maritime regulation: A well-to-wake evaluation of different propulsion scenarios. *Chem. Eng. J.* **2024**, *498*, 155407. [CrossRef]
6. Wan, Z.; Nie, A.; Chen, J.; Pang, C.; Zhou, Y. Transforming ports for a low-carbon future: Innovations, challenges, and opportunities. *Ocean Coast. Manag.* **2025**, *264*, 107636. [CrossRef]
7. Wang, Z.; Countryman, A.M. Island economies in the wake: Assessing increased shipping cost effects from carbon taxes on maritime trade. *Resour. Conserv. Recycl.* **2025**, *219*, 108325. [CrossRef]
8. Ramsay, W.; Fridell, E.; Michan, M. Maritime energy transition: Future fuels and future emissions. *J. Mar. Sci. Appl.* **2023**, *22*, 681–692. [CrossRef]
9. Park, S.; Lee, H.; Kim, D. Regulatory compliance and operational efficiency in maritime transport: Strategies and insights. *Transp. Policy* **2024**, *155*, 161–177. [CrossRef]
10. Sun, M.; Vortia, M.P.; Xiao, G.; Yang, J. Carbon policies and liner speed optimization: Comparisons of carbon trading and carbon tax combined with the european union emissions trading scheme. *J. Mar. Sci. Eng.* **2025**, *13*, 204. [CrossRef]
11. Yuan, Q.; Wang, S.; Peng, J. Operational efficiency optimization method for ship fleet to comply with the carbon intensity indicator (CII) regulation. *Ocean Eng.* **2023**, *286*, 115487. [CrossRef]
12. Meng, L.; Liu, K.; He, J.; Han, C.; Liu, P. Carbon emission reduction behavior strategies in the shipping industry under government regulation: A tripartite evolutionary game analysis. *J. Clean. Prod.* **2022**, *378*, 134556. [CrossRef]
13. He, Y.; Yan, X.; Fan, A.; Yin, X.; Meng, Q.; Zhang, L.; Liu, P. Assessing the influence of actual LNG emission factors within the EU emissions trading system. *Transp. Policy* **2024**, *159*, 345–358. [CrossRef]
14. Wu, M.; Li, K.X.; Xiao, Y.; Yuen, K.F. Carbon Emission Trading Scheme in the shipping sector: Drivers, challenges, and impacts. *Mar. Policy* **2022**, *138*, 104989. [CrossRef]
15. Cascajo, R.; Molina-Sánchez, R.; Diaz-Hernandez, G. Use of model-based weather forecasting systems for validation of areas for marine energy deployment in port service areas. *Appl. Sci.* **2025**, *15*, 4948. [CrossRef]
16. Dong, J.; Zeng, J.; Yang, Y.; Wang, H. A review of law and policy on decarbonization of shipping. *Front. Mar. Sci.* **2022**, *9*, 1076352. [CrossRef]
17. Luo, X.; Yan, R.; Wang, S. After five years' application of the European Union monitoring, reporting, and verification (MRV) mechanism: Review and prospectives. *J. Clean. Prod.* **2024**, *434*, 140006. [CrossRef]
18. Wu, Y.; Wen, K.; Zou, X. Impacts of shipping carbon tax on dry bulk shipping costs and maritime trades—The case of China. *J. Mar. Sci. Eng.* **2022**, *10*, 1105. [CrossRef]
19. Takebayashi, K. The effects of vertical integration and carbon tax on supply chain performance and economic welfare in the maritime industry. *Marit. Policy Manag.* **2025**, *52*, 208–228. [CrossRef]
20. Ding, W.; Wang, Y.; Dai, L.; Hu, H. Does a carbon tax affect the feasibility of arctic shipping? *Transp. Res. Part D Transp. Environ.* **2020**, *80*, 102257. [CrossRef]
21. Cariou, P.; Halim, R.A.; Rickard, B.J. Ship-owner response to carbon taxes: Industry and environmental implications. *Ecol. Econ.* **2023**, *212*, 107917. [CrossRef]
22. Mundaca, G. Short-and long-term effects of carbon taxation on the prices of products shipped by sea. *Energy Policy* **2023**, *193*, 114292. [CrossRef]
23. Jin, J.; Meng, L.; Wang, X.; He, J. Carbon emission reduction strategy in shipping industry: A joint mechanism. *Adv. Eng. Inform.* **2024**, *62*, 102728. [CrossRef]
24. Kotzampasakis, M. Maritime emissions trading in the EU: Systematic literature review and policy assessment. *Transp. Policy* **2025**, *165*, 28–41. [CrossRef]
25. Hellström, M.; Rabetino, R.; Schwartz, H.; Tsvetkova, A.; Haq, S.H.U. GHG emission reduction measures and alternative fuels in different shipping segments and time horizons–a delphi study. *Mar. Policy* **2024**, *160*, 105997. [CrossRef]
26. Issa, M.; Ilinca, A.; Martini, F. Ship energy efficiency and maritime sector initiatives to reduce carbon emissions. *Energies* **2022**, *15*, 7910. [CrossRef]
27. Rony, Z.I.; Mofijur, M.; Hasan, M.M.; Rasul, M.G.; Jahirul, M.I.; Ahmed, S.F.; Kalam, M.A.; Badruddin, I.A.; Khan, T.Y.; Show, P.L. Alternative fuels to reduce greenhouse gas emissions from marine transport and promote UN sustainable development goals. *Fuel* **2023**, *338*, 127220. [CrossRef]
28. Sjerić, M.; Perčić, M.; Jovanović, I.; Vladimir, N. Carbon footprint and economic analysis of lng-fueled fishing vessel using real engine performance simulation. *J. Mar. Sci. Appl.* **2025**, *24*, 1–18. [CrossRef]
29. Xing, H.; Stuart, C.; Spence, S.; Chen, H. Alternative fuel options for low carbon maritime transportation: Pathways to 2050. *J. Clean. Prod.* **2021**, *297*, 126651. [CrossRef]
30. Cullinane, K.; Yang, J. Evaluating the costs of decarbonizing the shipping industry: A review of the literature. *J. Mar. Sci. Eng.* **2022**, *10*, 946. [CrossRef]

31. Chen, S.; Zheng, S.; Sys, C. Policies focusing on market-based measures towards shipping decarbonization: Designs, impacts and avenues for future research. *Transp. Policy* **2023**, *137*, 109–124. [CrossRef]
32. Hero, M.; Vidmar, P.; Vlačič, P.; Perkovič, M. Limiting greenhouse gas emissions in the maritime transport sector. *Transp. Res. Procedia* **2025**, *83*, 157–164. [CrossRef]
33. Peng, H.; Wang, M.; An, C. Implied threats of the Red Sea crisis to global maritime transport: Amplified carbon emissions and possible carbon pricing dysfunction. *Environ. Res. Lett.* **2024**, *19*, 074053. [CrossRef]
34. Gössling, S.; Meyer-Habighorst, C.; Humpe, A. A global review of marine air pollution policies, their scope and effectiveness. *Ocean Coast. Manag.* **2021**, *212*, 105824. [CrossRef]
35. Wang, W.; Zou, Y.; Cheng, Y.; Liu, Y. The impact of EU-ETS on the global marine industry and the relevant investment dispute resolutions. *Front. Mar. Sci.* **2024**, *11*, 1333809. [CrossRef]
36. Dominioni, G.; Petit, C.A. Carbon pricing for international shipping and border carbon adjustment mechanisms: A case for regulatory cooperation. *Eur. J. Risk Regul.* **2025**, *16*, 133–148. [CrossRef]
37. Trosvik, L.; Brynolf, S. Decarbonising Swedish maritime transport: Scenario analyses of climate policy instruments. *Transp. Res. Part D Transp. Environ.* **2024**, *136*, 104457. [CrossRef]
38. Govindan, K.; Dua, R.; Anwar, A.M.; Bansal, P. Enabling net-zero shipping: An expert review-based agenda for emerging techno-economic and policy research. *Transp. Res. Part E Logist. Transp. Rev.* **2024**, *192*, 103753. [CrossRef]
39. Flodén, J.; Zetterberg, L.; Christodoulou, A.; Parsmo, R.; Fridell, E.; Hansson, J.; Rootzén, J.; Woxenius, J. Shipping in the EU emissions trading system: Implications for mitigation, costs and modal split. *Clim. Policy* **2024**, *24*, 969–987. [CrossRef]
40. Wang, J.; Zhu, W. Analyzing the development of competition and cooperation among ocean carriers considering the impact of carbon tax policy. *Transp. Res. Part E Logist. Transp. Rev.* **2023**, *175*, 103157. [CrossRef]
41. Alamoush, A.S.; Ölçer, A.I.; Ballini, F. Ports' role in shipping decarbonization: A common port incentive scheme for shipping greenhouse gas emissions reduction. *Clean. Logist. Supply Chain* **2022**, *3*, 100021. [CrossRef]
42. Jia, J.; Qian, C.; Dong, Y.; Li, Y.F.; Wang, H.; Ghoussoub, M.; Butler, K.T.; Walsh, A.; Ozin, G.A. Heterogeneous catalytic hydrogenation of CO 2 by metal oxides: Defect engineering–perfecting imperfection. *Chem. Soc. Rev.* **2017**, *46*, 4631–4644. [CrossRef]
43. Song, J.; Xu, C.; Wang, C. Impacts of the carbon tax on green shipping supply chain under the port competition. *Expert Syst.* **2024**, *41*, e13229. [CrossRef]
44. Sahoo, P.B.B.; Thakur, V. The factors obstructing the blockchain adoption in supply chain finance: A hybrid fuzzy DELPHI-AHP-DEMATEL approach. *Int. J. Qual. Reliab. Manag.* **2024**, *41*, 2292–2310. [CrossRef]
45. Hosseini, S.M.; Soltanpour, Y.; Paydar, M.M. Applying the delphi and fuzzy DEMATEL methods for identification and prioritization of the variables affecting Iranian citrus exports to Russia. *Soft Comput.* **2022**, *26*, 9543–9556. [CrossRef]
46. Gupta, S.; Gupta, N. Enhancing freight logistics: Overcoming barriers and driving sustainable growth with an integrated grey delphi DEMATEL approach. *Benchmarking Int. J.* **2025**, *ahead-of-print*. [CrossRef]
47. Shanta, M.H.; Choudhury, I.A.; Salman, S. Municipal solid waste management: Identification and analysis of technology selection criteria using fuzzy delphi and fuzzy DEMATEL technique. *Heliyon* **2024**, *10*, e23236. [CrossRef] [PubMed]
48. Shah, J.K.; Sharma, M.; Gunasekaran, A.; Joshi, S. Modeling critical enablers of hydrogen supply chains for decarbonization: Insights from emerging economies. *Sustain. Futures* **2025**, *9*, 100519. [CrossRef]
49. Liu, W.; Hu, Y.; Huang, Q. Research on critical factors influencing organizational resilience of major transportation infrastructure projects: A hybrid fuzzy DEMATEL-ISM-MICMAC approach. *Buildings* **2024**, *14*, 1598. [CrossRef]
50. He, R.; Xing, W.; Chai, Z.; Zhang, X. A Method for Identifying and Assessing Operational Risk Factors of Road Freight E-Commerce Platforms with Multi-Dimensional and Multi-Level Characteristics. *Systems* **2025**, *13*, 167. [CrossRef]
51. Wang, S.; Wang, J.; Wang, X. Risk analysis of human evacuation aboard passenger ships based on fuzzy DEMATEL-ISM-BN. *Ocean Eng.* **2024**, *313*, 119520. [CrossRef]
52. Qian, Y.; Wang, H. Vulnerability assessment for port logistics system based on DEMATEL-ISM-BWM. *Systems* **2023**, *11*, 567. [CrossRef]
53. Chang, B.; Chang, C.W.; Wu, C.H. Fuzzy DEMATEL method for developing supplier selection criteria. *Expert Syst. Appl.* **2011**, *38*, 1850–1858. [CrossRef]
54. Bafail, O.; Alamoudi, M. Prioritizing Worker-Related Factors of Safety Climate Using Fuzzy DEMATEL Analysis. *Systems* **2025**, *13*, 383. [CrossRef]
55. Hanay, U.; İnce, H.; Işık, G. Identifying Key Factors of Reputational Risk in Finance Sector Using a Linguistic Fuzzy Modeling Approach. *Systems* **2024**, *12*, 440. [CrossRef]
56. Liu, Z.; Wang, N.; Du, Q. The Governance of PPP Project Resilience: A Hybrid DMATEL-ISM Approach. *Systems* **2025**, *13*, 277. [CrossRef]
57. Arıcan, O.H.; Ünal, A.U. Risk Assessment in LPG and LNG operation processes in maritime transport: Delphi and fault tree analysis approach. *Processes* **2025**, *13*, 1136. [CrossRef]

58. Alqahtani, F.M.; Noman, M.A. An Integrated Fuzzy Delphi and Fuzzy AHP Model for Evaluating Factors Affecting Human Errors in Manual Assembly Processes. *Systems* **2024**, *12*, 479. [CrossRef]
59. Alqahtani, F.M.; Noman, M.A.; Alabdulkarim, S.A.; Alharkan, I.; Alhaag, M.H.; Alessa, F.M. A new model for determining factors affecting human errors in manual assembly processes using fuzzy delphi and dematel methods. *Symmetry* **2023**, *15*, 1967. [CrossRef]
60. Arican, O.H. Optimal tugboat placement in narrow straits for ship safety: A fuzzy delphi and P-Median approach, as exemplified by the Dardanelles Strait. *Ships Offshore Struct.* **2025**, *20*, 1–13. [CrossRef]
61. Ruano, M.; Huang, C.Y.; Nguyen, P.H.; Nguyen, L.A.T.; Le, H.Q.; Tran, L.C. Enhancing sustainability in Belize's ecotourism sector: A fuzzy Delphi and fuzzy DEMATEL investigation of key indicators. *Mathematics* **2023**, *11*, 2816. [CrossRef]
62. Mohammadfam, I.; Khajevandi, A.A.; Dehghani, H.; Babamiri, M.; Farhadian, M. Analysis of factors affecting human reliability in the mining process design using fuzzy delphi and DEMATEL methods. *Sustainability* **2022**, *14*, 8168. [CrossRef]
63. Lin, R.J. Using fuzzy DEMATEL to evaluate the green supply chain management practices. *J. Clean. Prod.* **2013**, *40*, 32–39. [CrossRef]
64. Wu, W.W.; Lee, Y.T. Developing global managers' competencies using the fuzzy DEMATEL method. *Expert Syst. Appl.* **2007**, *32*, 499–507. [CrossRef]
65. Wang, X.; Zhou, M.; Su, M. Critical Success Factors for Enhancing Intelligent Loading and Unloading in Urban Supply Chains: A Comprehensive Approach Based on Fuzzy DEMATEL-AISM-MICMAC. *Systems* **2025**, *13*, 230. [CrossRef]
66. Ünal, A.U.; Arıcan, O.H. Accident risk analysis of gas tankers in maritime transport using an integrated fuzzy approach. *Appl. Sci.* **2025**, *15*, 6008. [CrossRef]
67. Wang, M.J.J.; Chang, T.C. Tool steel materials selection under fuzzy environment. *Fuzzy Sets Syst.* **1995**, *72*, 263–270. [CrossRef]
68. Li, R.J. Fuzzy method in group decision making. *Comput. Math. Appl.* **1999**, *38*, 91–101. [CrossRef]
69. Liao, C.H. AI Product Factors and Pro-Environmental Behavior: An Integrated Model with Hybrid Analytical Approaches. *Systems* **2025**, *13*, 144. [CrossRef]
70. Pei, R.; Chen, M.; Liu, Z. Identifying Key Digital Enablers for Urban Carbon Reduction: A Strategy-Focused Study of AI, Big Data, and Blockchain Technologies. *Systems* **2025**, *13*, 646. [CrossRef]
71. European Commission. FuelEU Maritime: Reducing Greenhouse Gas Emissions from Ships. 2023. Available online: https://transport.ec.europa.eu/transport-themes (accessed on 9 October 2025).
72. IMO. Net-Zero Framework for International Shipping. International Maritime Organization, 2025. Available online: https://www.imo.org/en/OurWork/Environment/Pages/NetZero.aspx (accessed on 9 October 2025).
73. Port of Rotterdam. Building a Sustainable Port. Port of Rotterdam Authority, 2025. Available online: https://www.portofrotterdam.com/en/building-port/sustainable-port (accessed on 9 October 2025).
74. Port of Rotterdam. ECT Terminals Switching to Shore Power, Reducing $CO_2$ Emissions. Port of Rotterdam Authority, 2025. Available online: https://www.portofrotterdam.com/en/news-and-press-releases/ect-terminals-switching-shore-power-reducing-co2-emissions-approx-35000 (accessed on 9 October 2025).
75. Port of Rotterdam. Innovation in the Port of the Future. Port of Rotterdam Authority, 2025. Available online: https://www.portofrotterdam.com/en/port-future/innovation (accessed on 9 October 2025).


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.