sustainability

MDPI

Article

Empirical Analysis of Barriers to Collaborative Information Sharing in Maritime Logistics Using Fuzzy AHP Approach

Chang-Woo Lee [1], Dong-Gyun Sohn [1], Min-Gyu Sang [1,*] and Chulung Lee [2,*]

[1] Department of Industrial and Management Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea; 2023010188@korea.ac.kr (C.-W.L.); 2023010519@korea.ac.kr (D.-G.S.)
[2] School of Industrial and Management Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea
* Correspondence: tkdalsrb@korea.ac.kr (M.-G.S.); leecu@korea.ac.kr (C.L.)

Abstract: Collaborative information sharing in the maritime logistics supply chain is essential for achieving efficiency, sustainability, and resilience. However, numerous barriers hinder effective information sharing among key stakeholders, including port operators, shipping companies, and trucking firms. This study conducts an empirical analysis involving surveys and interviews with logistics industry experts in South Korea, applying the Fuzzy Analytical Hierarchy Process (Fuzzy AHP) to identify and prioritize critical collaborative information-sharing barriers in the maritime logistics supply chain. Through a comprehensive literature review, a range of barriers was identified, and their relevance was validated through structured surveys with industry experts. The application of Fuzzy AHP, which incorporates the inherent uncertainty in human judgment, enabled the identification of the most critical barriers that require urgent resolution. Based on these findings, a robust and actionable framework is proposed to address the identified challenges, integrating insights from expert interviews and the literature. The framework encompasses strategies such as data standardization, advanced data security, enhanced service compatibility, policy and institutional improvements, and stakeholder engagement. By addressing these critical barriers, the proposed framework aims to foster seamless information sharing and collaboration, ultimately enhancing the efficiency and sustainability of the maritime logistics supply chain.

Keywords: maritime logistics; supply chain collaboration; information sharing; analytic hierarchy process

check for updates

Academic Editors: Vitor Caldeirinha, Manuela Batista and Pedro Teodoro

Received: 26 November 2024
Revised: 13 February 2025
Accepted: 14 February 2025
Published: 19 February 2025

Citation: Lee, C.-W.; Sohn, D.-G.; Sang, M.-G.; Lee, C. Empirical Analysis of Barriers to Collaborative Information Sharing in Maritime Logistics Using Fuzzy AHP Approach. *Sustainability* **2025**, *17*, 1721. https://doi.org/10.3390/su17041721

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

In the dynamic realm of maritime logistics, the seamless integration and sharing of information among stakeholders, including port operators, shipping companies, and truck companies, are pivotal for fostering efficiency and driving competitive advantages. The intricate web of logistics activities requires a harmonized approach where every entity within the supply chain collaborates effectively to meet the overarching goals of cost reduction, customer satisfaction, and operational excellence. Information sharing, as a cornerstone of supply chain management, enables stakeholders to overcome the inherent complexities of maritime logistics by promoting transparency and fostering collaboration. It has been shown that information collaboration significantly enhances reverse logistics performance, indicating that these practices are essential for optimizing supply chain operations beyond traditional buyer–supplier relationships [1]. This is particularly relevant

in maritime logistics, where the integration of diverse entities is crucial for managing multifaceted transportation and distribution processes effectively.

The ability of port operators to perform as logistics centers is contingent upon their capacity to integrate with other supply chain actors. The importance of viewing ports through a logistics and supply chain management lens to develop relevant performance frameworks has been emphasized in previous studies [2]. This approach not only underscores the necessity for information sharing but also highlights the benefits of collaborative strategies in enhancing port efficiency through value-added logistics activities. For instance, collaboration between shipping companies and port operators can also lead to more efficient container handling and reduced fuel consumption for ships. This cooperative approach, where shipping lines compensate port operators for higher handling rates, ultimately minimizes supply chain costs and improves transportation [3]. Moreover, coordinated management methods for information contracts in port logistics service supply chains improve the scheduling and identification processes, enhancing the overall coordination capabilities [4].

Furthermore, the advent of technologies such as blockchain has underscored the importance of data transparency and secure information exchange among logistics stakeholders. In response to this need, recent studies have proposed blockchain-based financing schemes that utilize smart contract technology to enhance information flow while ensuring privacy protection [5]. Such technological advancements are pivotal in addressing the challenges of data sharing in logistics, thereby facilitating smoother interactions between shipping companies and other stakeholders.

The critical nature of supply chain logistics information collaboration (SCLIC) has been further explored in recent studies, which propose an evolutionary game theory-based strategy to enhance SCLIC [6]. This strategy emphasizes the importance of information collaboration in achieving supply chain success, highlighting the necessity for stakeholders to engage in collaborative decision-making processes that optimize logistics operations. In the context of maritime logistics, collaborative advantage emerges as a significant outcome of supply chain collaboration (SCC), leading to improved port performance. Studies have established a positive correlation between SCC and port performance, advocating for inter-organizational collaboration practices as a means to amplify collaborative advantage in the maritime supply chain [7]. This perspective aligns with the broader view that logistics and supply chain integration serve as pivotal drivers of competitiveness [8].

As shown in the numerous literature and case studies, the imperative for information and data sharing among key stakeholders in maritime logistics cannot be overstated. By embracing collaborative frameworks and leveraging advanced technologies, stakeholders can significantly enhance operational efficiency, reduce costs, and achieve superior service quality. Such collaborative endeavors not only optimize individual logistics processes but also contribute to the holistic improvement of the maritime logistics landscape. Currently, although there is a growing recognition that cooperative information sharing in the maritime logistics sector is important, it is not widely practiced in the field. Therefore, in this paper, we intend to identify which barriers currently exist and what are the critical barriers that require urgent resolution through analytic hierarchy process analysis of various maritime logistics stakeholders. Moreover, through expert interviews, we also suggest strategies to resolve such barriers and address the numerous benefits of collaborative logistics.

2. Literature Review

The efficient functioning of maritime supply chains hinges critically on the effective sharing of data and information among key stakeholders, including port authorities,

shipping companies, and truck companies. Effective collaborative information sharing helps reduce operational redundancies, improve resource allocation, and enable real-time decision-making [9,10]. Technologies like Port Community Systems (PCS), blockchain, and Artificial Intelligence (AI) have shown significant potential in improving the visibility and synchronization of supply chains [11,12]. However, implementing collaboration often encounters multiple challenges that hinder its full realization. The following studies highlight several barriers that interrupt effective collaboration in the maritime supply chain.

1. Cultural and Organizational Barriers: Cultural differences, misaligned objectives, and resistance to change are common barriers among stakeholders. For instance, port authorities may prioritize operational throughput, whereas shipping companies focus on cost minimization, leading to conflicts in collaboration efforts [13]. Additionally, the absence of leadership to drive collaborative efforts exacerbates the issue [14].
2. Technological Barriers: Technological disparities among stakeholders create a fragmented environment. Smaller players, such as trucking firms, often lack the resources to invest in advanced technologies, while larger stakeholders may operate incompatible systems [15]. The high cost of IT infrastructure and maintenance further limits the adoption of collaborative platforms like PCS [16]. Moreover, the lack of standardized communication protocols complicates data integration across the supply chain [9].
3. Regulatory Barriers: Collaboration is frequently hindered by inconsistent regulations and overlapping jurisdictions. Port authorities often operate under stringent government mandates, which may conflict with private-sector practices [10]. Bureaucratic hurdles, such as lengthy approval processes for data sharing, also contribute to delays and inefficiencies [17].
4. Trust Deficit: Stakeholders are often reluctant to share sensitive information due to concerns about data misuse or exploitation [18]. Past incidents of data breaches and the lack of transparency in information-sharing agreements have further deepened the trust deficit [12]. Trust is a critical enabler of collaboration and requires significant effort to establish and maintain.
5. Economic Barriers: Financial constraints are a significant barrier, especially for smaller stakeholders. High investment costs for collaborative systems and unequal cost-sharing mechanisms among stakeholders discourage participation in joint initiatives [19]. Limited access to funding further exacerbates the digital divide within the industry [20].
6. Data Security and Privacy Concerns: The increasing reliance on digital platforms has heightened concerns over data security. Issues such as cyberattacks, data breaches, and ambiguous data ownership rights present substantial risks to collaboration [9,11].
7. Operational Barriers: Operational inefficiencies, including misaligned schedules and capacity constraints at ports and terminals, reduce the effectiveness of collaboration. Poor integration of multimodal transport systems further limits seamless cargo movement [10].

Addressing the various barriers to collaboration in maritime logistics requires a multifaceted approach tailored to the unique challenges of the industry. Cultural and organizational alignment is fundamental, as misaligned objectives and resistance to change often undermine collaborative efforts. Rodrigue and Notteboom highlight the importance of joint strategic planning to align the priorities of diverse stakeholders, while Hofmann and Bosshard emphasize the role of leadership in driving a collaborative culture [13,14]. Cross-stakeholder training and workshops can also help stakeholders understand mutual benefits and foster trust.

Technological advancements are critical in bridging gaps between stakeholders with varying levels of digital infrastructure. Standardized platforms like Port Community Sys-

tems (PCS) have been effective in integrating operations and streamlining data exchange [9]. However, the high costs associated with implementing such systems remain a challenge, particularly for smaller players. Yuen et al. suggest cloud-based solutions as a cost-effective alternative, while Lun et al. advocate for subsidies and financial incentives to encourage technology adoption across the supply chain [15,16].

Regulatory inconsistencies also require targeted solutions. Harmonizing regulations across jurisdictions can reduce inefficiencies and simplify collaboration. Lam and Zhang propose international frameworks that establish common standards for data sharing and operational practices [10]. Zhou et al. highlight the need for streamlined governance structures to minimize bureaucratic hurdles [17]. Song and Panayides explore the integration of global supply chains with port and terminal operations to enhance competitiveness, while Lai et al. examine how institutional isomorphism drives the adoption of information technology in supply chain management, emphasizing the role of regulatory, normative, and market pressures in technological standardization [21,22].

Building trust is another essential aspect of overcoming barriers to collaboration. Transparency in data sharing can be enhanced through the utilization of blockchain technology, which provides secure and immutable records of shared information [12]. Additionally, Zhao et al. stress the importance of establishing clear legal agreements to mitigate fears of data misuse and ensure equitable treatment of all stakeholders [18]. Regular communication and joint decision-making processes further contribute to trust-building.

Economic barriers, such as the unequal distribution of costs, can be addressed through public–private partnerships and shared cost models. Notteboom suggests that collaborative financing mechanisms can help distribute costs more equitably, ensuring the participation of resource-constrained players [19]. Notteboom et al. argue that governments can play a pivotal role by offering tax incentives or grants for stakeholders investing in collaborative systems [20].

Lastly, operational and environmental challenges require innovative solutions. Predictive analytics and AI can improve scheduling and operational efficiency, helping to align stakeholder activities and reduce capacity constraints at ports [12]. In the context of environmental sustainability, collaborative efforts to co-fund green technologies and adopt energy-efficient practices are crucial for meeting stringent regulatory requirements [13]. Núñez-Merino et al. explored the application of quantum-inspired computing technology in operations and logistics management, highlighting its potential to enhance complex decision-making and improve real-time problem-solving in dynamic logistics environments [23]. By addressing these barriers through a combination of technological, regulatory, and cultural strategies, the maritime logistics industry can achieve more effective and sustainable collaboration.

Table 1 summarizes various barriers and overcoming strategies in past literature. Once those barriers are eliminated and successfully implemented, collaborative information and data sharing can create a synergistic environment that enhances overall supply chain performance. Therefore, it is important to identify the priorities of current barriers and strategically handle each of them.

Table 1. Barriers and Solutions of Maritime Supply Chain Collaboration.

Barrier Category	Specific Barriers	Solutions to Overcome	References
Cultural and Organizational	- Misaligned objectives between stakeholders (e.g., cost efficiency vs. throughput). - Resistance to change within organizations. - Lack of leadership in driving collaboration.	- Develop joint strategic goals to align priorities. - Conduct cross-stakeholder training and workshops to build a collaborative culture. - Encourage leadership involvement in collaboration.	[10,13,14]
Technological	- Lack of standardization in systems and protocols. - Gaps in technology adoption, especially among smaller players. - High implementation and maintenance costs of IT systems.	- Implement standardized platforms like Port Community Systems (PCS). - Provide subsidies or incentives for technology adoption by smaller firms. - Offer cloud-based cost-efficient solutions.	[9,15,16]
Regulatory	- Inconsistent regulations across regions. - Bureaucratic hurdles in data sharing approvals. - Overlapping jurisdiction among port authorities and government agencies.	- Harmonize international regulations to streamline collaboration. - Establish policies to simplify data-sharing agreements. - Create unified governance frameworks for port operations.	[10,17,21]
Trust Deficit	- Fear of data misuse or exploitation by competitors. - Lack of transparency in collaborative practices. - Past incidents of data breaches undermining trust	- Use blockchain technology for secure and transparent data sharing. - Establish legal frameworks and agreements to ensure fair use of shared information. - Increase stakeholder communication.	[11,12,18]
Economic	- Financial constraints on implementing collaborative systems. - Unequal cost-sharing among stakeholders. - Limited access to funding for smaller players.	- Create public–private partnerships to share infrastructure costs. - Introduce tax benefits or grants for stakeholders investing in collaborative systems. - Explore shared cost models.	[9,19,20]
Data Security and Privacy	- Concerns over data breaches and cyberattacks. - Limited technical expertise in data security management. - Ambiguity in data ownership and control rights.	- Enhance cybersecurity measures and implement data encryption. - Provide training in data security practices. - Define data ownership policies in contracts.	[11,22]
Operational	- Inefficiencies in aligning schedules among stakeholders. - Capacity constraints at ports and terminals. - Poor integration of multimodal transport systems.	- Use AI and machine learning for predictive scheduling. - Optimize terminal layouts and operations for higher capacity. - Develop interconnected transport systems for seamless operations. - Adoption of quantum-inspired computing technology for flexibility and operational agility.	[10,12,13,23]

3. Methodology

3.1. Deriving Collaborative Information-Sharing Barriers in Maritime Logistics from the Literature Review

Based on the above literature review and additional interviews with experts from the maritime logistics industry, we investigated and categorized current barriers to collaborative information sharing in the maritime supply chain. The barriers are organized in Table 2.

Table 2. Main and Sub-Categorized Barriers.

Top-Level Barriers	Sub-Category	Explanation
Regulatory and Policy Barriers	Lack of Governance Agreements (LGA)	The absence of governance agreements, such as contracts, can make it difficult to hold partners and coordinators accountable for their responsibilities.
	Difficulty in Agreeing on Cost/ Profit-Sharing Policies (DACPSP)	Some companies may disagree with specific policies, perceiving them as insufficiently aligned with their own interests.
	Lack of Trust in the Coordinator (LTC)	Partners may hesitate to agree on contracts if they suspect that the managing entity could propose unfavorable terms.
	Inadequate Government Support (IGS)	Without active government initiatives, such as facilitating collaboration or easing regulations, companies may find it burdensome to pursue collaborative efforts.
Data Quality and Standardization Barriers	Asymmetrical Information Distribution (AID)	Unequal access to information among supply chain actors hampers efficient decision-making.
	Lack of Timely Information Updates (LTIU)	Delayed information updates can adversely affect decision-making processes, reducing efficiency.
	Low Information Accuracy (LIA)	Inaccurate information can significantly diminish the effectiveness of collaboration.
	Lack of Information Interoperability (LII)	When data are presented in incompatible formats, additional processing is required, hindering collaboration.
	Lack of Common Standards for Shared Data (LCSSD)	The absence of universally accepted standards for technology and data formats leads to inconsistencies in shared data.
	Absence of Information/ Data Sharing Platform (AIDSP)	The lack of a dedicated platform for data sharing can impede collaboration and increase costs.
Knowledge, Behavior, and Attitude of Stakeholders	Failing to Keep Commitments (FKC)	Partners may fail to fulfill their responsibilities or adhere to agreed profit-sharing terms in a collaborative supply chain.
	Lack of Trust among Partners (LTP)	Trust issues may arise between competitors within a shared platform, affecting cooperation.
	Unawareness of the Collaboration Benefits (UCB)	Managers may lack awareness of the economic, social, and environmental advantages of collaboration, reducing its perceived necessity.
	Misconception of Collaborative Supply Chain Aims and Technologies (MCSCAT)	Some companies may misunderstand the technologies and methodologies involved in collaborative supply chains.
	Resistance to Change (RC)	Stakeholders may be reluctant to adopt new practices or technologies.
Internal Organizational Barriers	Lack of Trained Employees and Training Systems (LTETS)	A shortage of personnel and training systems for data management and utilization may obstruct collaboration.
	Lack of Communication (LC)	Inadequate communication culture and systems within organizations can hinder collaboration. This is particularly significant for small- and medium-sized enterprises (SMEs).
	Data Security/Privacy Issues (DSPI)	Concerns over security and privacy may prevent organizations from sharing information internally or externally.
	Limited IT Infrastructure (LITI)	Limited IT infrastructure can restrict the implementation of robust security solutions, risk management tools, and effective data collection and utilization.
Cross-Organizational Barriers	Cultural Resistance to Collaborate (CRC)	Cultural differences between organizations can negatively impact cross-organizational interactions.
	Unequal Cost-Sharing among Stakeholders (UCSS)	When the distribution of costs among project stakeholders is unfair, stakeholders may not want to participate.
	Risk of System Conversion (RSC)	Transitioning from existing systems to new collaborative frameworks entails financial and operational risks.

3.2. Identification of Critical Barriers Using Analytical Hierarchy Process

The paper proposes a fuzzy Analytical Hierarchy Process (AHP) approach to identify the priority of different barriers to collaborative information sharing in maritime logistics. AHP and Fuzzy AHP have been successfully applied in various fields such as supply chain management, project prioritization, and infrastructure planning. Their ability to incorporate subjective judgments makes them suitable for complex decision-making environments. For example, Sunil et al. applied these methods to evaluate barriers to adopting sustainable consumption and production initiatives in SCM [24]. Additionally, Wang et al. utilized Fuzzy AHP in selecting third-party logistics providers in the Industry 4.0 context, demonstrating its capability to manage uncertainty in industrial applications [25].

While the AHP and Fuzzy AHP are widely utilized in multi-criteria decision-making due to their structured approach and ability to incorporate expert judgment, their inherent limitations often necessitate the adoption of alternative MCDA methods. The computational complexity of Fuzzy AHP, particularly in fuzzification and defuzzification processes, can further limit its practical applicability in large-scale decision environments, leading to the preference for Best-Worst Method (BWM), which requires fewer comparisons and maintains higher consistency [26]. Moreover, methods like ELECTRE and TOPSIS are often favored for ranking large sets of alternatives due to their ability to directly assess performance scores rather than relying on hierarchical structuring [27]. Similarly, Fuzzy RANCOM has gained attention as an efficient rank-ordering approach that reduces computational intensity while preserving decision-making accuracy [28]. While BWM and Fuzzy RANCOM provide computational efficiency, they may not fully accommodate the hierarchical relationships among barriers, which are critical in this study. Therefore, Fuzzy AHP was selected as the most suitable method for analyzing the multi-layered and uncertain nature of collaborative information-sharing barriers in the maritime supply chain.

3.2.1. Analytical Hierarchy Process

AHP is a popular multi-criteria decision-making (MCDM) tool introduced by Saaty. It seeks to measure the relative importance of a set of alternatives using a ratio scale, relying on the decision-maker's assessments. It emphasizes the value of intuitive judgments and the need for consistent comparisons between alternatives throughout the decision-making process [29]. The AHP involves the following steps:

(1) Problem Definition and Hierarchy Structuring: The decision problem is decomposed into a hierarchical structure consisting of the goal, criteria, sub-criteria, and alternatives.

(2) Pairwise Comparisons: Decision-makers perform pairwise comparisons of criteria and alternatives based on their relative importance concerning the goal. This is usually conducted using a scale of absolute judgments. In this study, A pairwise comparison is performed using a 1–9 scale proposed by Saaty to compare the relative importance of two elements. Detailed description of each scale is shown in Table 3.

For n criteria, the comparison matrix A is defined as

$$A = \begin{pmatrix} 1 & a_{12} & a_{13} & \dots & a_{1n} \\ \frac{1}{a_{12}} & 1 & a_{23} & \dots & a_{2n} \\ \frac{1}{a_{13}} & \frac{1}{a_{23}} & 1 & \dots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \frac{1}{a_{3n}} & \dots & 1 \end{pmatrix}$$

Table 3. Importance Scale for AHP pair-wise comparison.

Importance Numbers (a_{ij})	Value	Meaning
1	Equal	*i* and *j* are equally important
3	Moderately more important	*i* is moderately more important than *j*
5	Strongly more important	*i* is strongly more important than *j*
7	Very strongly more important	*i* is very strongly more important than *j*
9	Extremely more important	*i* is extremely more important than *j*
2, 4, 6, 8	Intermediate values	Used for compromise between the two adjacent judgments

(3) Priority Weight Calculation: The relative weights for criteria and alternatives are calculated using eigenvalue methods, resulting in a priority vector. Here, λ_{max} is the largest eigenvalue of A.

$$A \cdot \omega = \lambda_{max} \cdot \omega$$

(4) Consistency Check: The consistency of judgments is verified through the Consistency Ratio (CR). If CR is above a certain threshold, the decision-makers are encouraged to revise their judgments [30]. It is computed as

$$CR = \frac{CL}{RI}$$

where

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

and RI is the Random index. CR value below 0.1 is considered acceptable.

3.2.2. Prioritization of Collaborative Information-Sharing Barriers in Maritime Logistics

In traditional AHP, decision-makers are required to provide precise numerical values when making pairwise comparisons between criteria, which can be difficult when the criteria involve complex, interdependent, or qualitative factors. However, in real-world scenarios, especially in the maritime industry, stakeholder judgments are often imprecise, influenced by diverse experiences, organizational contexts, and varying levels of expertise. Therefore, we implement a fuzzy AHP approach for identifying collaborative information-sharing barriers in the maritime logistics supply chain.

Fuzzy AHP integrates fuzzy logic, introduced by Zadeh, into AHP to address uncertainty in pairwise comparisons [31]. The fuzzy AHP technique is considered an enhanced analytical approach that evolved from the traditional AHP. It replaces crisp values with fuzzy numbers, typically triangular fuzzy numbers (TFNs), to capture the ambiguity in human preferences. For example, in the pairwise comparison matrix, each element a_{ij} can be expressed as a triangular fuzzy number $\widetilde{a}_{ij}$= (l_{ij}, m_{ij}, u_{ij}). Here, l_{ij} represents the minimum value, m_{ij} is the middle value, and u_{ij} is the maximum value. The membership function $\mu(x)$ is defined as:

$$\mu(x) = \begin{cases} 0 & if\ x < l \\ \frac{x-l}{m-l} & if\ l \le x \le m \\ \frac{u-x}{u-m} & if\ m \le x\ \le u \\ 0 & if\ x > u \end{cases}$$

The converted values are assigned fuzzy scales in the form of TFNs to create a fuzzy pairwise comparison matrix. Then, the sum of fuzzy values for each row is normalized to

derive fuzzy weights, and final priorities are derived by applying the centroid method to defuzzify the fuzzy weights.

$$\omega = \frac{l + m + u}{3}$$

In this study, fuzzy analytic hierarchy process (AHP) questionnaires were answered by various maritime logistics industry sector experts including terminal operators, shipping companies, and truck companies to identify the priority ranking of barriers. Fuzzy AHP provides a structured, reliable, and analytically rigorous approach to identifying and prioritizing information-sharing barriers in maritime logistics. While alternative MCDA methods such as the Best–Worst Method (BWM) and Fuzzy RANCOM offer computational simplicity, they may lack the hierarchical depth and nuanced weight assessment capabilities required for analyzing complex maritime logistics environments. Therefore, the use of Fuzzy AHP in this study aligns with the methodological needs of the research.

4. Results

To ensure the reliability of the pairwise comparison matrices used in the Fuzzy AHP analysis, λ-max, Consistency Index (CI), and Consistency Ratio (CR) were calculated. As shown in Table 4, all CR values were below the acceptable threshold of 0.1, indicating sufficient consistency in the expert judgments. The high consistency across matrices ensures the robustness of the analysis results.

Table 4. Consistency Index and Ratio for Fuzzy AHP Evaluation of Barriers to Collaboration by Category.

Category	λ-Max	CI	CR
Overall Barriers to Collaboration	5.164	0.04107	0.03667
Regulatory and Policy Barriers	4.035	0.01160	0.01289
Data Quality and Standardization Barriers	6.085	0.01704	0.01374
Knowledge, Behavior and Attitude of Stakeholders	5.065	0.01613	0.01440
Internal Organizational Barriers	4.068	0.02266	0.02517
Cross-Organizational Barriers	3.008	0.00406	0.00701

4.1. Fuzzy AHP Analysis for Top-Level Barriers

The analysis evaluated the relative importance of five top-level barriers to data integration: Knowledge, Behavior, and Attitude of Stakeholders, Internal Organizational Barriers, Regulatory and Policy Barriers, Data Quality and Standardization Barriers, and Cross-Organizational Barriers. The results, expressed as defuzzified weights, are summarized in Table 5.

Table 5. Fuzzy AHP Analysis for Top-Level Barriers and Their Relative Importance.

Top-Level Barrier	Fuzzy Weight (L, M, U)	Defuzzified Weight	Rank
Knowledge, Behavior and Attitude of Stakeholders	[0.3, 0.37, 0.45]	0.373	1
Data Quality and Standardization Barriers	[0.17, 0.22, 0.26]	0.217	2
Regulatory and Policy Barriers	[0.17, 0.21, 0.25]	0.21	3
Cross-Organizational Barriers	[0.09, 0.11, 0.13]	0.11	4
Internal Organizational Barriers	[0.07, 0.09, 0.11]	0.09	5

The most critical barrier identified is the Knowledge, Behavior, and Attitude of Stakeholders. This criterion ranks first, emphasizing the crucial role of stakeholder dynamics in overcoming challenges. Aligning stakeholder attitudes, behaviors, and knowledge with

organizational goals is paramount to achieving effective solutions. Organizations must focus on strategies such as stakeholder engagement, training, and collaboration to address this priority area.

The second most significant barrier are Data Quality and Standardization Barriers. This finding underscores the importance of implementing robust data governance frameworks and standardization processes to ensure reliable and interoperable data systems. Addressing this barrier will facilitate better decision-making and streamline operations, particularly in complex environments involving multiple stakeholders and systems.

Regulatory and Policy Barriers rank third. This result highlights the influence of external regulatory and policy frameworks on the system's efficiency. Proactive compliance strategies, policy advocacy, and active dialog with regulatory authorities are essential to mitigate the challenges posed by this barrier.

The fourth-ranking barrier is Cross-Organizational Barriers. While less critical compared to the top three barriers, cross-organizational challenges still warrant attention. Effective communication, collaboration, and alignment of goals across organizations are necessary to ensure the seamless functioning of the overall system.

Finally, Internal Organizational Barriers rank fifth. These barriers, while the least significant in this analysis, should not be overlooked. Addressing internal issues such as workflow inefficiencies, resource constraints, and organizational silos can enhance overall performance and reduce internal friction.

4.2. Fuzzy AHP Analysis for Sub-Category Barriers

4.2.1. Fuzzy AHP Results for Regulatory and Policy Barriers

The pairwise comparison matrix for the sub-categories within the 'Regulatory and Policy Barriers' category is provided in the table below (Table 6), offering a detailed representation of the relative importance of each sub-category. The term of each sub-category is abbreviated for convenience.

Table 6. Pairwise Comparison Matrix for Sub-Categories within Regulatory and Policy Barriers.

Sub Category	DACPSP	LTC	IGS	LGA
DACPSP	1	0.382	0.693	1
LTC	2.621	1	2.621	1.817
IGS	1.442	0.382	1	1.101
LGA	1	0.55	0.909	1

The results of the Fuzzy AHP analysis, which includes the fuzzy weights and defuzzified weights for each sub-category, are provided in Table 7. These results, derived from the pairwise comparison matrix for the sub-categories under 'Regulatory and Policy Barriers', offer a detailed representation of the relative importance of each sub-category.

Table 7. Fuzzy AHP Analysis for Sub-Categories of Regulatory and Policy Barriers: Importance Ranking.

Sub Category	Fuzzy Weight (L, M, U)	Defuzzified Weight	Rank
DACPSP	[0.30, 0.40, 0.50]	0.400	1
LTC	[0.25, 0.30, 0.35]	0.300	2
IGS	[0.20, 0.25, 0.30]	0.250	3
LGA	[0.15, 0.20, 0.25]	0.200	4

The Fuzzy AHP analysis identified Difficulty in Agreeing on Cost/Profit Sharing Policies as the most critical sub-category, with a defuzzified weight of 0.400. This result emphasizes the urgent need for harmonized policy frameworks and agreements among stakeholders to ensure smooth collaboration and decision-making processes. Addressing

this barrier requires a focus on creating cohesive policies and fostering alignment across diverse organizational objectives to facilitate efficient collaboration.

The second most significant sub-category is Lack of Trust in the Coordinator, with a defuzzified weight of 0.300. This highlights the importance of building trust in coordinators by ensuring clear communication, transparency in decision-making processes, and well-defined roles and responsibilities. Trust-building measures can play a pivotal role in enhancing stakeholder collaboration and reducing conflicts, ensuring that coordination efforts are perceived as fair and reliable.

Inadequate Government Support, with a defuzzified weight of 0.250, ranks as the third most critical barrier. This sub-category underscores the necessity of governmental involvement to facilitate policy alignment and provide adequate resources and guidance. Effective support from governing bodies can significantly enhance the implementation of collaborative initiatives and help overcome policy-related challenges. Governments play a central role in fostering an environment conducive to public–private partnerships, creating regulations, and offering financial incentives.

Lastly, Lack of Governance Agreements, with a defuzzified weight of 0.200, is ranked as the least critical sub-category. While its importance is relatively lower, it remains significant as it emphasizes the need for formalized contracts and well-defined governance mechanisms. These elements are essential for ensuring accountability, protecting stakeholders' interests, and fostering sustainable collaboration over time. Formal agreements can help mitigate risks associated with unclear roles, expectations, and responsibilities among partners.

This hierarchical ranking of barriers provides actionable insights for prioritizing interventions to address policy-related challenges effectively. By focusing on the most critical issues—such as policy alignment, trust-building, and government support—stakeholders can enhance the effectiveness of collaborative initiatives and improve overall coordination within the industry.

4.2.2. Fuzzy AHP Results for Data Quality and Standardization Barriers

The pairwise comparison matrix for the sub-categories within the 'Data Quality and Standardization Barriers' category is provided in Table 8, offering a detailed representation of the relative importance of each sub-category.

Table 8. Pairwise Comparison Matrix for Sub-Categories within Data Quality and Standardization Barriers.

Sub Category	AID	LTIU	LIA	LII	LCSSD	AIDSP
AID	1	1.442	1.587	1.442	0.794	1.26
LTIU	0.693	1	1.077	0.763	0.721	1.17
LIA	0.63	0.928	1	0.437	0.347	0.63
LII	0.693	1.31	2.289	1	0.5	1.101
LCSSD	1.26	1.387	2.884	2	1	1.442
AIDSP	0.794	0.855	1.587	0.909	0.693	1

The results of the Fuzzy AHP analysis, which includes the fuzzy weights and defuzzified weights for each sub-category, are provided in Table 9. These results, derived from the pairwise comparison matrix for the sub-categories under 'Data Quality and Standardization Barriers' offer a detailed representation of the relative importance of each sub-category.

Table 9. Fuzzy AHP Analysis for Sub-Categories of Data Quality and Standardization Barriers: Importance Ranking.

Sub Category	Fuzzy Weight (L, M, U)	Defuzzified Weight	Rank
LCSSD	[0.30, 0.40, 0.50]	0.400	1
LII	[0.25, 0.35, 0.45]	0.350	2
AID	[0.20, 0.30, 0.40]	0.300	3
LTIU	[0.15, 0.25, 0.35]	0.250	4
AIDSP	[0.10, 0.20, 0.30]	0.200	5
LIA	[0.05, 0.15, 0.25]	0.150	6

The analysis of sub-categories under "Data Quality and Standardization Barriers" revealed that Lack of Common Standards for Shared Data is the most critical barrier, with a defuzzified weight of 0.400. This finding emphasizes the importance of establishing standardized data-sharing protocols to enhance interoperability and ensure accuracy in collaborative data practices. Without such standards, organizations face significant challenges in integrating and utilizing data effectively, as the lack of a common framework leads to inconsistencies and inefficiencies in shared data.

Lack of Information Interoperability, with a defuzzified weight of 0.350, emerged as the second-most significant barrier. This reflects the pressing need for seamless communication between disparate systems to enable smooth and efficient data integration. When data are presented in incompatible formats, additional processing is required, which hinders collaboration and introduces inefficiencies. Addressing this issue through the adoption of universal communication protocols is essential for fostering more effective data-sharing across different systems.

The third-ranked barrier, Asymmetrical Information Distribution (defuzzified weight: 0.300), highlights the challenges posed by uneven access to information among stakeholders. This imbalance impedes collaborative decision-making processes, often leading to mistrust and inefficiencies in multi-stakeholder environments. Ensuring equal access to relevant data are critical for improving collaboration and ensuring that all parties involved have the necessary information to make informed decisions.

Lack of Timely Information Updates, with a defuzzified weight of 0.250, was identified as the fourth-most critical sub-category. Limited real-time updates reduce the overall efficiency of data-sharing mechanisms, particularly in time-sensitive operations, where delays in information flow can result in operational inefficiencies. To enhance the effectiveness of collaborative efforts, stakeholders must prioritize systems that enable the real-time exchange of information and ensure that all participants are working with up-to-date data.

The absence of Information/Data Sharing Platforms ranked fifth with a defuzzified weight of 0.200, pointing to the absence of shared platforms for data exchange. While less critical than other barriers, the lack of infrastructure for centralized data sharing remains a significant challenge that can hinder collaboration and data utilization. Developing dedicated platforms for data sharing would improve collaboration, streamline data exchange processes, and reduce collaboration costs.

Finally, Low Information Accuracy was identified as the least critical sub-category. While it ranked lowest, ensuring data accuracy remains essential to maintain the reliability and trustworthiness of data-driven processes. Poor data quality can undermine the validity of decisions, decrease operational efficiency, and reduce stakeholder confidence in collaborative efforts. Ensuring accurate data is fundamental for making informed decisions and fostering trust among stakeholders.

These findings highlight the multi-faceted nature of barriers to data quality and standardization. Addressing the most critical issues, such as the Lack of Common Standards for Shared Data and Lack of Information Interoperability, will be key to fostering effective data-sharing environments and improving collaborative efficiency. By focusing on these

areas, stakeholders can mitigate the challenges posed by uneven data access, lack of interoperability, and outdated or inaccurate information, ultimately enhancing the overall effectiveness of collaborative initiatives.

4.2.3. Fuzzy AHP Results for Knowledge, Behavior, and Attitude of Stakeholders

The pairwise comparison matrix for the sub-categories within the 'Knowledge, Behavior, and Attitude of Stakeholders' category is provided in Table 10, offering a detailed representation of the relative importance of each sub-category.

Table 10. Pairwise Comparison Matrix for Sub-Categories within Knowledge, Behavior, and Attitude of Stakeholders.

Sub Category	FKC	LTP	UCB	MCSCAT	RC
FKC	1	0.794	0.281	1.26	1.101
LTP	1.26	1	0.347	2.289	2.52
UCB	3.557	2.884	1	3.557	3.634
MCSCAT	0.794	0.437	0.281	1	0.794
RC	0.909	0.397	0.275	1.26	1

The results of the Fuzzy AHP analysis, which includes the fuzzy weights and defuzzified weights for each sub-category, are provided in Table 11. These results, derived from the pairwise comparison matrix for the sub-categories under 'Knowledge, Behavior, and Attitude of Stakeholders' offer a detailed representation of the relative importance of each sub-category.

Table 11. Fuzzy AHP Analysis for Sub-Categories of Knowledge, Behavior, and Attitude of Stakeholders Barriers: Importance Ranking.

Sub Category	Fuzzy Weight (L, M, U)	Defuzzified Weight	Rank
UCB	[0.35, 0.40, 0.45]	0.400	1
LTP	[0.28, 0.32, 0.36]	0.320	2
FKC	[0.27, 0.31, 0.35]	0.310	3
RC	[0.23, 0.27, 0.30]	0.267	4
MCSCAT	[0.20, 0.25, 0.28]	0.243	5

The Fuzzy AHP analysis for sub-categories under "Knowledge, Behavior, and Attitude of Stakeholders" provides valuable insights into the relative importance of barriers in this category. The defuzzified weights and rankings, based on the fuzzy triangular weights (L, M, U), are as follows:

Ranked as the most critical sub-category, this barrier underscores the need for programs aimed at increasing stakeholder awareness of the advantages of collaboration. A lack of understanding regarding the potential benefits can significantly hinder collaborative initiatives, as stakeholders may not perceive the value of their participation. Addressing this barrier requires targeted education and outreach programs designed to demonstrate the tangible benefits of collaboration, such as improved efficiency, cost savings, and access to new opportunities.

Ranked second, Lack of Trust among Partners highlights the importance of building trust within collaborative relationships. Trust issues often stem from misaligned expectations, prior negative experiences, or insufficient communication. Building trust requires clear communication, transparency in decision-making, and well-defined roles and responsibilities. Promoting mutual accountability and fostering transparent processes are essential steps to mitigate this barrier and encourage effective collaboration.

Failure to Keep Commitments, which ranks closely with trust-related issues, reflects the significance of maintaining accountability within collaborative partnerships. Stakeholders may fail to fulfill their responsibilities or adhere to agreed-upon terms, disrupting the

collaborative process. Addressing this barrier requires the implementation of accountability mechanisms, formal agreements, and regular monitoring to ensure stakeholders honor their commitments and remain engaged in the collaboration.

Resistance to Change, ranked fourth, points to the challenges that arise when stakeholders are reluctant to adopt new systems, practices, or technologies. This barrier can arise from fear of failure, reluctance to alter established processes, or lack of understanding. Effective management strategies, including leadership support, training programs, and clear communication about the benefits of change, are crucial to overcoming resistance and ensuring smoother transitions.

Misunderstanding of Collaborative Supply Chain Aims and Technologies ranks as the least critical but still important barrier. Stakeholders may not fully understand the technologies or methodologies involved, leading to inefficiencies. Providing clear explanations, training, and educational support is essential to help stakeholders better understand the tools and processes involved in collaboration, ensuring successful technology adoption.

The Fuzzy AHP analysis reveals that "Unawareness of the Collaboration Benefits" is the most critical barrier under Stakeholder Perceptions and Attitudes. This finding emphasizes the need for targeted programs to raise awareness about the benefits of collaboration. "Lack of Trust among Partners" and "Failure to Keep Commitments" are also significant barriers, requiring efforts to improve transparency, accountability, and communication. Addressing and resolving "Resistance to Change" and "Misunderstanding of Collaborative Supply Chain Aims and Technologies" will further enhance collaboration effectiveness. By focusing on these priority areas, stakeholders can improve collaboration, foster trust, and drive successful partnerships in collaborative supply chains.

4.2.4. Fuzzy AHP Results for Internal Organizational Barriers

The pairwise comparison matrix for the sub-categories within the 'Internal Organizational Barriers' category is provided in Table 12, offering a detailed representation of the relative importance of each sub-category.

Table 12. Pairwise Comparison Matrix for Sub-Categories within Internal Organizational Barriers.

Sub Category	LTETS	LC	DSPI	LITI
LTETS	1	2.289	0.763	0.794
LC	0.437	1	0.55	0.794
DSPI	1.31	1.817	1	1
LITI	1.26	1.26	1	1

The results of the Fuzzy AHP analysis, which includes the fuzzy weights and defuzzified weights for each sub-category, are provided in Table 13. These results, derived from the pairwise comparison matrix for the sub-categories under 'Internal Organizational Barriers' offer a detailed representation of the relative importance of each sub-category.

Table 13. Fuzzy AHP Analysis for Sub-Categories of Internal Organizational Barriers: Importance Ranking.

Sub Category	Fuzzy Weight (L, M, U)	Defuzzified Weight	Rank
DSPI	[0.30, 0.40, 0.50]	0.400	1
LTETS	[0.25, 0.35, 0.45]	0.350	2
LITI	[0.20, 0.30, 0.40]	0.300	3
LC	[0.15, 0.25, 0.35]	0.250	4

The Fuzzy AHP analysis for sub-categories under "Internal Organizational Barriers" revealed the relative importance of various challenges. The defuzzified weights and rankings for the sub-categories are as follows:

Ranked as the most critical sub-category, this highlights the importance of addressing security risks to ensure safe and reliable data-sharing practices. The concern over data security, whether internal or external, is paramount to protecting sensitive information and ensuring that data sharing does not expose organizations to unnecessary risks. This barrier is significant in today's interconnected business environment, where data breaches and privacy concerns can undermine trust and collaboration. Mitigating this risk requires robust data security frameworks, encryption standards, and compliance with privacy regulations.

Ranked second, this barrier emphasizes the need for qualified personnel to manage and operate data systems effectively. Organizations face a shortage of skilled professionals who are capable of handling complex data systems and security protocols. This skills gap can impede effective collaboration, as it limits the ability to manage data, integrate systems, and address security concerns. Addressing this barrier requires investment in training programs, recruitment of skilled professionals, and continuous professional development to ensure that the workforce is equipped to handle evolving technological demands.

Ranked third, this barrier reflects challenges associated with outdated or inadequate IT infrastructure. These deficiencies can restrict the implementation of robust security solutions, risk management tools, and effective data collection and utilization. Without the right infrastructure, organizations may struggle to meet the demands of modern data integration and security. Upgrading IT systems, adopting scalable cloud solutions, and investing in system integration capabilities are key actions to address this barrier and enhance organizational readiness for data-driven collaboration.

Ranked fourth, this barrier highlights communication gaps within organizations. Poor communication can lead to misunderstandings, missed opportunities, and inefficiencies in data-sharing practices. Inadequate communication culture and systems can hinder collaboration, particularly in larger organizations or those operating across multiple locations. To overcome this barrier, organizations must prioritize clear communication channels, establish effective information-sharing platforms, and encourage a culture of open dialog across all levels of the organization.

The analysis identifies "Data Security Issues" as the most critical sub-category under "Internal Organizational Barriers". To address this, organizations need to develop and implement strong data protection measures, including encryption, access controls, and privacy safeguards. Additionally, addressing the lack of skilled professionals and IT infrastructure deficiencies is essential for supporting data management efforts and ensuring that collaboration can occur in a secure and efficient environment. Finally, improving internal communication will facilitate smoother data-sharing practices and enhance overall collaboration. By focusing on these key areas, organizations can mitigate internal barriers to data integration and collaboration, fostering more effective and secure data-driven decision-making processes.

4.2.5. Fuzzy AHP Results for Cross-Organizational Barriers

The pairwise comparison matrix for the sub-categories within the 'Cross-Organizational Barriers' category is provided in Table 14, offering a detailed representation of the relative importance of each sub-category.

Table 14. Pairwise Comparison Matrix for Sub-Categories within Cross-Organizational Barriers.

Sub Category	CRC	UCSS	RSC
CRC	1	3	1.26
UCSS	0.333	1	0.55
RSC	0.794	1.817	1

The results of the Fuzzy AHP analysis, which includes the fuzzy weights and defuzzified weights for each sub-category, are provided in Table 15. These results, derived from the pairwise comparison matrix for the sub-categories under 'Cross Organizational Barriers' offer a detailed representation of the relative importance of each sub-category.

Table 15. Fuzzy AHP Analysis for Sub-Categories of Cross-Organizational Barriers: Importance Ranking.

Sub Category	Fuzzy Weight (L, M, U)	Defuzzified Weight	Rank
CRC	[0.35, 0.40, 0.45]	0.400	1
UCSS	[0.30, 0.35, 0.40]	0.350	2
RSC	[0.25, 0.30, 0.35]	0.300	3

The Fuzzy AHP analysis for the sub-categories under Cross-Organizational Barriers highlights the critical challenges faced in fostering effective inter-organizational collaboration. The analysis prioritizes the barriers based on their defuzzified weights, as detailed below.

Ranked as the most critical barrier, cultural resistance emphasizes the challenges posed by differing organizational cultures. These differences can significantly hinder effective collaboration. Addressing this barrier requires cultural awareness programs, cross-organizational training, and a shared understanding of collaborative goals.

Ranked second, unequal cost-sharing represents a significant challenge. When the costs of a project are not distributed fairly among stakeholders, it may lead to dissatisfaction and reluctance to participate. Ensuring fair and transparent cost-sharing mechanisms is essential to fostering long-term, successful collaborations.

Ranked third, system conversion risks are particularly important in the context of transitioning from existing systems to more integrated collaborative frameworks. This shift introduces financial and operational risks, which require careful planning, resource allocation, and risk management strategies to minimize disruption during the transition.

The analysis identifies "Cultural Resistance to Collaborate" as the most significant barrier under Cross organizational barriers, followed by "Unequal Cost-Sharing among Stakeholders" and "Risk of System Conversion". Addressing these issues through targeted interventions such as cultural alignment programs, fair cost-sharing policies, and comprehensive system conversion strategies will be critical for fostering smoother collaboration between organizations. By focusing on these areas, organizations can enhance their collaborative efforts and mitigate the risks associated with inter-organizational collaboration.

4.2.6. Total Result of Fuzzy AHP Analysis

The analysis involved determining the relative importance of various sub-criteria under broader categories (or top-level criteria) by utilizing their defuzzified weights. The results shown in Figure 1 were obtained by multiplying the defuzzified weights of the top-level criteria with the corresponding weights of the sub-criteria. This approach allowed for a failure prioritization of the sub-criteria, providing insights into their significance within the overarching framework.

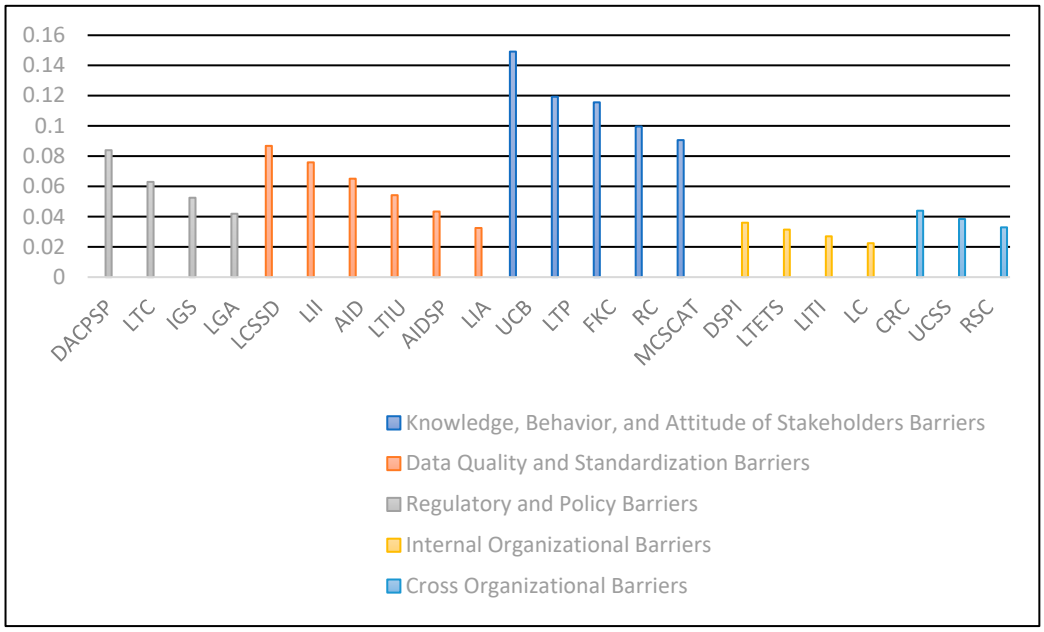


Figure 1. Priority Comparison of Total Barriers of Collaborative Information Sharing in Maritime Logistics.

Among the sub-categories, Unawareness of the Collaboration Benefits emerged as the most significant factor with a weight of 0.1492. This indicates that a lack of understanding regarding the potential benefits of collaboration is a major barrier to achieving effective cooperation among stakeholders. Similarly, Lack of Trust among Partners (0.11936) and Failure to Keep Commitments (0.11563) were identified as critical issues, highlighting the importance of fostering trust and ensuring reliability in collaborative efforts.

In contrast, sub-criteria such as Lack of Communication (0.0225), Limited IT Infrastructure (0.027), and Lack of Trained Employees and Training Systems (0.0315) were deemed relatively less significant. While these factors are not as critical as the top-ranking sub-criteria, they still contribute to the overall barriers and warrant attention to ensure a comprehensive strategy for addressing challenges. Table 16 summarizes the total ranking of each barrier.

Table 16. Priority Ranking of Total Barriers of Collaborative Information Sharing in Maritime Logistics.

Top-Level Barriers (Ranking)	Sub-Category	Ranking (Global)	Ranking (Local)
Regulatory and Policy Barriers (#3)	Lack of Governance Agreements (LGA)	15	4
	Difficulty in Agreeing on Cost/Profit-Sharing Policies (DACPSP)	7	1
	Lack of Trust in the Coordinator (LTC)	10	2
	Inadequate Government Support (IGS)	12	3

Table 16. *Cont.*

Top-Level Barriers (Ranking)	Sub-Category	Ranking (Global)	Ranking (Local)
Data Quality and Standardization Barriers (#2)	Asymmetrical Information Distribution (AID)	9	3
	Lack of Timely Information Updates (LTIU)	11	4
	Low Information Accuracy (LIA)	19	6
	Lack of Information Interoperability (LII)	8	2
	Lack of Common Standards for Shared Data (LCSSD)	6	1
	Absence of Information/Data Sharing Platform (AIDSP)	14	5
Knowledge, Behavior, and Attitude of Stakeholders (#1)	Failing to Keep Commitments (FKC)	3	3
	Lack of Trust among Partners (LTP)	2	2
	Unawareness of the Collaboration Benefits (UCB)	1	1
	Misconception of Collaborative Supply Chain Aims and Technologies (MCSCAT)	5	5
	Resistance to Change (RC)	4	4
Internal Organizational Barriers (#5)	Lack of Trained Employees and Training Systems (LTETS)	20	2
	Lack of Communication (LC)	22	4
	Data Security/Privacy Issues (DSPI)	17	1
	Limited IT Infrastructure (LITI)	21	3
Cross-Organizational Barriers (#4)	Cultural Resistance to Collaborate (CRC)	13	1
	Unequal Cost-Sharing among Stakeholders (UCSS)	16	2
	Risk of System Conversion (RSC)	18	3

4.2.7. Sensitivity Analysis

To ensure the robustness and reliability of the Fuzzy AHP results, a weight sensitivity analysis was conducted. This test involved systematically adjusting the barrier weights to observe potential ranking changes. To further assess the resilience of the rankings, a randomized perturbation approach was applied, where weights of barriers were modified randomly within a range of $\pm 5\%$ to $\pm 30\%$.

The results of the sensitivity analysis indicate the following key findings: for minor perturbations ($\pm 5\%$ to $\pm 10\%$), the rankings remained highly stable, with Spearman's Rank Correlation Coefficient exceeding 0.98 in all cases, suggesting a high level of robustness in the rankings. For moderate perturbations ($\pm 10\%$ to $\pm 20\%$), some barriers exhibited slight shifts in ranking, particularly those related to governance and policy constraints.

For larger perturbations (±20% to ±30%), significant changes in ranking were observed for certain barriers, demonstrating that they are more sensitive to weight variations than others. In particular, highly sensitive barriers include DACPSP (Difficulty in Agreeing on Cost/Profit Sharing Policies) and AID (Asymmetrical Information Distribution). These barriers require further evaluation, as their relative importance may shift depending on different operational or regulatory conditions. LGA (Lack of Governance Agreements), IGS (Inadequate Government Support), and LTC (Lack of Trust in the Coordinator) remained relatively stable across all perturbation levels. These barriers are likely to remain critical obstacles regardless of minor changes in weight assumptions. This analysis result is summarized in Table 17.

Table 17. Weight Sensitivity Analysis Result.

Barrier	Average Rank Change (5%)	Average Rank Change (15%)	Average Rank Change (30%)
LGA	0	0.5	1.5
DACPSP	3	3	4
LTC	0.5	1.5	4.5
IGS	0	1	2
AID	0.5	2.5	4.5
LTIU	0	0	1
LIA	1.5	3	4.5
LII	0	2	3
LCSSD	1	1	3
AIDSP	0	1	2
FKC	0	0	0
LTP	0	0	2
UCB	0	0	1
MCSCAT	2	2	5
RC	0	0	2
LTETS	0	1.5	1
LC	0	0.5	1
DSPI	0	1	3
LITI	0	0.5	2.5
CRC	1.5	2.5	2.5
UCSS	0	2.5	2.5
RSC	0	0	0.5

The findings confirm that while the Fuzzy AHP rankings are generally stable, certain barriers are more sensitive to weight variations, particularly those related to governance and regulatory constraints. This suggests that decision-makers should consider scenario-based evaluations to anticipate potential changes in priority under different operational conditions. Overall, the weight sensitivity test validates the robustness of the model while also highlighting the need for flexibility in addressing dynamic barriers in maritime logistics collaboration.

4.3. The Collaborative Maritime Supply Chain Framework

The Collaborative Maritime Supply Chain Framework addresses the critical barriers identified through the Analytical Hierarchy Process (AHP), aiming to provide a systematic and actionable solution to challenges obstructing efficient information sharing among port operators, shipping companies, and trucking firms. This framework was developed through an iterative process combining insights from expert interviews and an extensive literature review to ensure both practical applicability and theoretical robustness. The following sections detail the core components and strategic directions encompassed in the framework.

Moreover, to further address concerns regarding the subjectivity of expert opinions, this study incorporated insights from in-depth interviews with logistics professionals who manage global hub ports handling maritime container logistics. These experts emphasized that regional and cultural differences in logistics operations are relatively minimal due

to the standardized nature of container handling, equipment, and operational systems employed by global terminal operators. It was highlighted that major hub ports, including those in Europe, North America, and Asia, follow similar frameworks for collaborative information sharing due to the presence of multinational terminal operators that enforce global standards. While certain elements, such as automation levels and labor laws, may differ by region and country, the fundamental principles of data exchange, interoperability, and system integration remain largely uniform. These insights reinforce the argument that the collaborative information-sharing framework proposed in this study is not only applicable to South Korea but can also be extended globally. By integrating standardized practices and global best practices, the framework aims to facilitate seamless information flow and enhance cooperation among maritime logistics stakeholders worldwide.

4.3.1. Data Standardization

Data standardization is the foundation of the framework, enabling uniformity and interoperability across all stakeholders. This is achieved by developing common definitions for key data elements, implementing structured formats (e.g., JSON or XML), and utilizing data mapping protocols to harmonize disparate datasets. Data quality is continuously monitored to ensure reliability and consistency, facilitating integration between systems. This approach mitigates inefficiencies arising from inconsistent data formats, ensuring smooth information flow across the supply chain. Implementing standardized data formats across diverse stakeholders with different legacy systems can be difficult due to resistance to change and technological incompatibility. To overcome this, an incremental adoption strategy should be applied, where stakeholders migrate to standardized data formats gradually. Providing financial incentives and conducting joint training programs can encourage adoption.

4.3.2. Advanced Data Security

Recognizing the sensitivity of data shared among stakeholders, the framework incorporates advanced security measures. Blockchain technology is utilized to create immutable records, enhancing trust and transparency. Multi-layered security systems, including encryption and access control, are employed to prevent unauthorized access. Regular security audits and robust incident response plans are implemented to mitigate risks, ensuring the integrity and confidentiality of shared information. While blockchain and encryption enhance security, stakeholders may be reluctant to share data due to concerns about privacy, competition, and regulatory constraints. A multi-tiered access control mechanism should be implemented, allowing stakeholders to control what information they share and with whom. Additionally, international cybersecurity compliance frameworks can be developed to build trust among participants.

4.3.3. Enhanced Service Compatibility

To address technological disparities, the framework promotes the development of technologies compatible with existing systems, such as EDI (Electronic Data Interchange) and API (Application Programming Interface) platforms. Middleware solutions are adopted to facilitate interoperability between legacy and modern systems, while modular designs enable stakeholders to implement features incrementally. Cross-platform testing should be conducted before full-scale implementation to ensure seamless integration. Cross-platform testing ensures operational efficiency, minimizing disruptions during integration.

4.3.4. Policy and Institutional Improvements

Policy reforms and institutional support are vital for fostering collaboration. The framework proposes establishing national data agencies to mediate and manage shared

information, creating a centralized authority to oversee data governance. Simplified legal frameworks are introduced to reduce regulatory barriers, while financial incentives, such as subsidies and tax benefits, encourage stakeholders to adopt collaborative technologies. These measures address systemic barriers and promote alignment among diverse entities.

4.3.5. Stakeholder Engagement

Stakeholder engagement is integral to the framework, ensuring broad participation and support. Traditional solutions for improving information-sharing, such as standardized protocols and centralized platforms, have had limited success due to concerns over data security, competition, and regulatory fragmentation. A collaborative innovation model, where stakeholders collectively develop, test, and refine new technologies, can help bridge these gaps by fostering trust, improving technological compatibility, and demonstrating tangible benefits. Awareness campaigns are conducted to educate stakeholders on the economic, social, and environmental benefits of collaboration. Experiential programs and pilot projects demonstrate the framework's tangible advantages, while feedback mechanisms foster continuous improvement. Recognition and reward systems incentivize active participation, strengthening long-term collaboration. Establishing feedback loops and recognition systems can further incentivize stakeholder participation and long-term engagement.

The proposed Collaborative Maritime Supply Chain Framework delivers a wide range of operational, economic, and environmental benefits by addressing the critical barriers identified through the fuzzy-AHP analysis. One of the most significant advantages is the reduction in environmental and time costs. By optimizing truck appointment systems and transport schedules, the framework minimizes truck idling times, leading to lower fuel consumption and reduced greenhouse gas emissions. This not only aligns with global sustainability goals but also reduces operational delays, providing stakeholders with measurable time and cost savings. Furthermore, the introduction of streamlined processes through data standardization and enhanced service compatibility eliminates redundancies, reducing container rehandling rates and unnecessary manual interventions, thereby enhancing overall supply chain efficiency.

Another major benefit lies in cost savings achieved through improved resource allocation and the prevention of demurrage and storage fees. By facilitating real-time data sharing and better coordination among stakeholders, the framework ensures that resources such as labor, equipment, and storage facilities are used more efficiently. For example, port operators can better manage vessel berthing schedules, while trucking firms benefit from optimized routing and load planning. Shipping companies, in turn, avoid costly delays caused by misaligned schedules or unforeseen congestion. These savings contribute directly to the financial sustainability of all stakeholders involved.

The framework also strengthens supply chain resilience by enabling proactive disruption management. Real-time data sharing and enhanced service compatibility allow stakeholders to anticipate and mitigate potential risks, such as equipment failures, weather-related disruptions, or port congestion. This increased agility ensures continuity of operations, even under challenging conditions. Moreover, the framework fosters improved trust among stakeholders through transparent data governance and equitable cost-sharing mechanisms. By addressing longstanding concerns about data security and misuse, it creates a foundation for long-term collaboration and innovation within the maritime supply chain. Together, these benefits establish the framework as a comprehensive solution for building a more sustainable, efficient, and resilient maritime logistics ecosystem.

4.4. International Variations in Maritime Collaboration

Maritime logistics networks exhibit regional variations in how collaborative information-sharing frameworks are structured and implemented. These differences are shaped by economic policies, regulatory environments, technological adoption rates, and historical trade relationships.

European port clusters, such as those in the North Sea region (e.g., Rotterdam, Hamburg, Antwerp), have developed highly integrated collaboration frameworks, largely driven by the European Union's regulatory policies and digital infrastructure initiatives. The widespread use of Port Community Systems (PCS) has facilitated seamless data exchange between shipping companies, port authorities, customs, and inland transport operators. These ports emphasize transparency and interoperability, allowing for efficient coordination between diverse logistics stakeholders. Furthermore, standardized customs procedures and data-sharing protocols across multiple EU nations enable greater synchronization in cross-border trade.

In contrast, East Asian port clusters (e.g., Shanghai, Busan, Singapore) have demonstrated rapid technological advancements, leveraging automation, blockchain-based documentation systems, and AI-driven analytics to optimize operational efficiency. While these ports maintain high throughput capacities and innovation-led competitiveness, collaborative frameworks tend to be more fragmented due to variations in regulatory policies across different jurisdictions. Unlike their European counterparts, where collaboration is institutionalized through regional trade agreements and policy harmonization, Asian ports often operate within national regulatory boundaries, requiring bilateral agreements or industry-led standardization efforts to facilitate seamless data exchange.

Despite these structural differences, the increasing globalization of supply chains is pushing both European and Asian maritime clusters toward greater convergence in digital collaboration strategies. The growing adoption of smart port initiatives, which integrate real-time vessel tracking, predictive analytics, and blockchain-secured transactions, is fostering a more interconnected logistics ecosystem. However, regional differences in policy coordination, investment priorities, and industry adoption rates continue to influence the pace and effectiveness of these transitions. Addressing these variations through harmonized data governance frameworks and policy coordination will be critical for enhancing global maritime collaboration.

4.5. Case Study of Partial Implementation of the Collaborative Maritime Supply Chain Framework

The successful implementation of smart technologies in a major international container port in South Korea demonstrates the effectiveness of collaborative information-sharing strategies in optimizing port operations. Notably, several components of the Collaborative Maritime Supply Chain Framework proposed in this study have already been partially applied, contributing to significant operational improvements.

One of the key implementations aligning with the proposed framework is the standardization of data formats and integration of advanced digital platforms. The adoption of an integrated terminal operating system has facilitated real-time data exchange across gate, yard, and ship activities, aligning with the data standardization and enhanced service compatibility strategies outlined in this study. As a result, port operations have become more synchronized, leading to a 15% reduction in container dwell time and a 10% improvement in overall supply chain efficiency.

Additionally, the introduction of automated terminal operations reflects the integration of stakeholder-driven technological adoption, a key component of the stakeholder engagement strategy in the proposed framework. By leveraging automated cargo transfers

and advanced scheduling systems, productivity has increased by up to 20%, significantly reducing manual intervention and improving operational resilience.

Furthermore, the implementation of smart port initiatives at this port aligns with the policy and institutional improvements proposed in this study. Participation in national-level digitalization programs and regulatory support for smart logistics solutions have facilitated seamless collaboration among key stakeholders, demonstrating the potential of institutional coordination in enhancing port performance. A recent study confirmed that this international port ranks among the most efficient container terminals in South Korea, highlighting the tangible benefits of smart port integration and information-sharing frameworks [32].

The fact that such significant improvements have already been observed even with the partial adoption of the proposed framework suggests that fully integrated implementation could yield even greater benefits. By ensuring seamless interconnection across all framework components, ports can achieve higher operational efficiency, further reductions in environmental impact, and greater economic resilience. A fully implemented collaborative information-sharing framework would not only enhance supply chain performance but also support global efforts toward carbon reduction, resource optimization, and long-term sustainability in maritime logistics.

5. Conclusions

This study explored the critical barriers to collaborative information sharing in maritime logistics, combining insights from expert interviews and a rigorous Fuzzy Analytical Hierarchy Process (Fuzzy AHP) analysis. By addressing these barriers, the research aimed to pave the way for more efficient, sustainable, and resilient supply chain operations. The results highlight "knowledge, behavior, and attitude of stakeholders" as the most critical barrier at the top level, followed closely by "data quality and standardization barriers". These findings underscore the multifaceted nature of challenges in maritime logistics, emphasizing the importance of both human factors and technological readiness in fostering effective collaboration.

The prominence of "knowledge, behavior, and attitude of stakeholders" reflects the significant role of trust, awareness, and willingness to collaborate among maritime supply chain participants. Resistance to change, lack of awareness about the benefits of collaboration, and distrust among stakeholders are substantial hurdles that hinder progress. These barriers highlight the need for targeted stakeholder engagement strategies, such as awareness campaigns, educational initiatives, and experiential programs, to align stakeholder objectives and foster a culture of trust and mutual benefit.

Meanwhile, "data quality and standardization barriers" emphasize the technical challenges inherent in collaborative information sharing. Inconsistent data formats, low information accuracy, and a lack of interoperability among systems exacerbate inefficiencies and reduce the effectiveness of collaboration. Addressing these barriers requires robust data standardization frameworks, incorporating structured data formats, consistent quality monitoring, and tools for seamless data mapping. The need for globally aligned data standards is particularly crucial, as maritime logistics involves stakeholders operating across diverse regions and regulatory contexts.

To address these critical barriers, this study proposed a Collaborative Maritime Supply Chain Framework, integrating five key strategies: data standardization, advanced data security, enhanced service compatibility, policy and institutional improvements, and stakeholder engagement. This framework directly addresses both human and technical barriers, providing actionable solutions to facilitate seamless information sharing. By improving stakeholder awareness and alignment, enhancing data quality, and ensur-

ing technological interoperability, the framework fosters a holistic approach to resolving collaboration challenges.

The implications of these findings are both practical and theoretical. Practitioners in maritime logistics can use the framework to implement targeted interventions, such as trust-building measures, training programs, and investments in interoperable technologies, to improve collaboration. Policymakers are encouraged to support these efforts by reforming regulations, incentivizing standardization efforts, and establishing centralized data governance bodies to oversee collaborative initiatives. For researchers, this study highlights the importance of integrating both behavioral and technical perspectives in future investigations of maritime logistics challenges.

Beyond these practical and theoretical implications, the findings of this study also underscore the broader regional, economic, and environmental dimensions of collaborative information sharing in maritime logistics. While differences in regulatory frameworks and technological adoption influence collaboration models across global port clusters, increasing digitalization is driving a shift toward greater interoperability and standardization. Ensuring that these advancements contribute not only to operational efficiency but also to supply chain resilience, sustainability, and workforce development remains a critical challenge. Addressing these aspects through harmonized policies, investment in digital infrastructure, and adaptive workforce strategies will be essential for fostering a more inclusive and future-ready maritime logistics ecosystem.

Despite its contributions, this study acknowledges certain limitations. The empirical analysis was conducted with a focus on South Korea, which, while offering valuable insights, may not fully represent the global maritime logistics landscape. Future research should expand the scope to include broader regional contexts and diverse industry stakeholders. Exploring the integration of emerging technologies such as blockchain and quantum computing into the proposed framework could enhance its scalability and applicability across complex logistics networks. Additionally, assessing the long-term socioeconomic impacts of automation in maritime logistics will be crucial to ensuring that technological advancements contribute to sustainable job creation and equitable workforce transitions. By addressing both regional collaboration challenges and social implications, future studies can further enhance the adaptability and resilience of global maritime logistics networks.

In conclusion, the findings of this study reaffirm the critical importance of addressing both stakeholder-related and technical barriers in maritime logistics. By prioritizing knowledge, behavior, and attitude challenges alongside data quality and standardization issues, the proposed framework offers a comprehensive pathway for overcoming collaborative barriers. This research contributes a practical roadmap for fostering trust, improving data reliability, and enhancing operational efficiency, ultimately driving the maritime logistics industry toward a more collaborative and sustainable future.

Author Contributions: C.-W.L.: performed conceptualization, funding acquisition, and the writing of the original manuscript; D.-G.S.: contributed to the methodology, investigation, formal analysis and writing of the original manuscript. M.-G.S.: contributed to the conceptualization, methodology, investigation, supervision, and writing of the original manuscript. C.L.: contributed to project administration, supervision, validation, and editing of the original manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the BK21 FOUR funded by the Ministry of Education of Korea and National Research Foundation of Korea. This research was also supported by the "Leaders in Industry-university Cooperation 3.0" Project, supported by the Ministry of Education and National Research Foundation of Korea.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Inquiries or requests about the questionnaire or specific analysis process can be directed to the corresponding author/s.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Olorunniwo, F.O.; Li, X. Information sharing and collaboration practices in reverse logistics. *Supply Chain Manag. Int. J.* **2010**, *15*, 454–462. [CrossRef]
2. Bichou, K.; Gray, R. A logistics and supply chain management approach to port performance measurement. *Marit. Policy Manag.* **2004**, *31*, 47–67. [CrossRef]
3. Liu, Z.; Wang, S.; Du, Y.; Wang, H. Supply chain cost minimization by collaboration between liner shipping companies and port operators. *Transp. J.* **2016**, *55*, 296–314. [CrossRef]
4. Duan, C.; Xiu, G.; Zhang, Y. Coordinated management method of information contract in port logistics service supply chain. *J. Coast. Res.* **2019**, *93*, 1047–1052. [CrossRef]
5. Zheng, K.; Zheng, L.J.; Gauthier, J.; Zhou, L.; Xu, Y.; Behl, A.; Zhang, J.Z. Blockchain technology for enterprise credit information sharing in supply chain finance. *J. Innov. Knowl.* **2022**, *7*, 100256. [CrossRef]
6. Zhang, Z.; Xue, Y.; Li, J.; Gong, L.; Wang, L. Supply chain logistics information collaboration strategy based on evolutionary game theory. *IEEE Access* **2020**, *8*, 46102–46120.
7. Seo, Y.-J.; Dinwoodie, J.; Roe, M. The influence of supply chain collaboration on collaborative advantage and port performance in maritime logistics. *Int. J. Logist. Res. Appl.* **2016**, *19*, 562–582. [CrossRef]
8. Mellat-Parast, M.; Spillan, J.E. Logistics and supply chain process integration as a source of competitive advantage: An empirical analysis. *Int. J. Logist. Manag.* **2014**, *25*, 289–314. [CrossRef]
9. Heilig, L.; Schwarze, S.; Voß, S. An analysis of digital transformation in the history and future of modern ports. *Comput. Ind.* **2017**, *87*, 12–22.
10. Lam, J.S.L.; Zhang, W. Enhancing supply chain resilience in maritime logistics: A decision-making framework. *Transp. Res. E* **2014**, *68*, 81–97.
11. Zhou, X.; Xu, X.; He, Y. Blockchain technology in maritime logistics. *Transp. Res. E* **2020**, *137*, 101966. [CrossRef]
12. Kuo, S.-Y.; Huang, X.-R.; Chen, L.-B. Smart ports: Sustainable smart business port operation schemes based on the Artificial Intelligence of Things and blockchain technologies. *IEEE Potentials* **2022**, *41*, 32–37. [CrossRef]
13. Rodrigue, J.-P.; Notteboom, T. The terminalization of supply chains: Reassessing port-hinterland logistical relationships. *Marit. Policy Manag.* **2009**, *36*, 165–183. [CrossRef]
14. Hofmann, E.; Bosshard, C. Supply chain collaboration in logistics: The role of trust and leadership. *Int. J. Phys. Distrib. Logist. Manag.* **2017**, *47*, 738–762.
15. Lun, V.Y.H.; Wong, E.; Lai, K.-H. Technology adoption and maritime logistics innovation. *Int. J. Ship. Transp. Logist.* **2021**, *13*, 300–317.
16. Yuen, K.F.; Wang, X.; Ma, F.; Wong, Y.D. The role of trust in facilitating collaborative innovation in maritime logistics. *Transp. Res. E* **2018**, *117*, 34–49.
17. Zhou, Q.; Lai, K.-h.; Wang, Q. Customization of information-sharing agreements in maritime logistics. *Int. J. Prod. Econ.* **2008**, *113*, 808–816.
18. Zhao, M.; Droge, C.; Stank, T.P. The effects of logistics capabilities on firm performance: Customer-focused versus information-focused capabilities. *J. Bus. Logist.* **2013**, *24*, 39–57. [CrossRef]
19. Notteboom, T.E. From multi-porting to hub porting: The adaptive capacity of container ports in a changing environment. *Int. J. Ship. Transp. Logist.* **2010**, *2*, 174–193.
20. Notteboom, T.; Pallis, A.; Rodrigue, J.-P. Green port governance. In *Port Economics, Management an d Policy*; Routledge: London, UK; New York, NY, USA, 2021; pp. 340–355.
21. Song, D.-W.; Panayides, P.M. Global supply chain and port/terminal: Integration and competitiveness. *Marit. Policy Manag.* **2008**, *35*, 73–87. [CrossRef]
22. Lai, K.-h.; Wong, C.W.Y.; Cheng, T.C.E. Institutional isomorphism and the adoption of information technology for supply chain management. *Comput. Ind.* **2013**, *64*, 262–271. [CrossRef]
23. Núñez-Merino, M.; Maqueira-Marín, J.M.; Moyano-Fuentes, J.; Castaño-Moraga, C.A. Quantum-inspired computing technology in operations and logistics management. *Int. J. Phys. Distrib. Logist. Manag.* **2024**, *54*, 247–274. [CrossRef]
24. Luthra, S.; Mangla, S.K.; Xu, L.; Diabat, A. Using AHP to evaluate barriers in adopting sustainable consumption and production initiatives in a supply chain. *Int. J. Prod. Econ.* **2016**, *181*, 342–349. [CrossRef]

25. Wang, C.-N.; Dang, T.-T. Third-party logistics provider selection in the Industry 4.0 era by using a fuzzy AHP and fuzzy MARCOS methodology. *IEEE Access* 2024, *in press*. [CrossRef]
26. Rezaei, J. Best-worst multi-criteria decision-making method. *Omega* **2015**, *53*, 49–57. [CrossRef]
27. Luthra, S.; Govindan, K.; Kannan, D.; Mangla, S.K.; Garg, C.P. An integrated framework for sustainable supplier selection and evaluation in supply chains. *J. Clean. Prod.* **2017**, *140*, 1686–1698. [CrossRef]
28. Więckowski, J.; Kizielewicz, B.; Sałabun, W. Fuzzy RANCOM: A novel approach for modeling uncertainty in decision-making processes. *Inf. Sci.* **2025**, *694*, 121716. [CrossRef]
29. Saaty, T.L. Priority setting in complex problems. *IEEE Trans. Eng. Manag.* **1983**, *3*, 140–155. [CrossRef]
30. Falsini, D.; Fondi, F.; Schiraldi, M.M. A logistics provider evaluation and selection methodology based on AHP, DEA and linear programming integration. *Int. J. Prod. Res.* **2012**, *50*, 4822–4829. [CrossRef]
31. Zadeh, L.A. Fuzzy sets. *Inf. Control* **1965**. [CrossRef]
32. Zhou, L.; Suh, W. A Comprehensive Study on Static and Dynamic Operational Efficiency in Major Korean Container Terminals Amid the Smart Port Development Context. *Sustainability* **2024**, *16*, 5288. [CrossRef]

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.