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Leveraging Blockchain for Maritime Port Supply Chain Management through Multicriteria Decision Making

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Abstract: This research investigates the optimal integration of Blockchain Technology (BT) in Supply Chain Management (SCM) within Chile's maritime ports. Utilizing fuzzy Logarithmic Methodology of Additive Weights (LMAW) and Double Normalization-based Multiple Aggregation Methods (DNMA), the study systematically identifies, prioritizes, and ranks key factors influencing BT adoption in SCM. The study's findings highlight crucial factors like enhanced transaction security, good supply chain practices, and risk management. Furthermore, it ranks the application of ports as prime candidates for BT integration. The research contributes theoretically by developing a hybrid model combining MCDA methods, and practically by guiding the strategic application of BT in the maritime logistics sector, aligning with the principles of Industry 5.0. This paper presents a novel approach that explores the utilization of BT in maritime supply chain management, incorporating MCDA in a vague environment. The research gap of this study lies in defining new contexts in both theoretical and practical literature reviews for extending the use of BT in SCM in the ports of Chile, according to Industry 5.0, to increase the efficiency and effectiveness of all aspects of operations in these places. The contribution of this research is applying hybrid MCDA methods in an uncertain environment to assist decision-makers (DMs) in better implementing BT in SCM in Chilean ports, according to Industry 5.0.

Keywords: blockchain port logistics; multicriteria decision analysis; industry 5.0; supply chain management

MSC: 90B50

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1. Introduction

Seaports are configured as complex systems where physical interactions and information exchanges are established between multiple actors, whether public or private. These actors perform various functions related to operational and logistical activities that are important for the daily functioning of the port operator [1]. They range from the supervision of security at port terminals, the control of goods by state entities, to the storage, consolidation, stacking, stowage, stevedoring, and transport of containers [1,2].

Each port is part of an integrated logistics chain for the export and import of perishable and non-perishable goods. The type of product that transits through port facilities depends on the competitive advantages of the exporting country's producers. Ports play a strategic role for a country, and in response to increasing international demands, they have incorporated sustainable environmental policies into their strategies and operations that require the implementation of an advanced level of technology [3]. This dynamic has driven the evolution of the industry over the port generations. Importantly, the transformation towards the smart industry differs in nature from the changes observed over the traditional port generations [4].

The concept of "smart port" is used in research due to the adoption of Industry 4.0 principles [5]. It describes a system characterized by its commitment to environmental sustainability, efficiency in logistics operations, pursuit of cost-effectiveness, and attention to the relationship with the urban environment [1,6].

In response to macro-environment transformations, ports have evolved by integrating cyber, technological, and sustainable elements into their logistics chains [4]. This not only improves information and communication systems in logistics chains but also contributes, for example, to the preservation of the environment by adopting cleaner energy sources [7]. On the other hand, in the micro-environment, both Port and Terminal Managers focus on achieving efficient management in aspects related to security, operations, and traceability of goods [2,8].

It is important to note that the definition of a "smart port" lacks consensus due to its complexity [9]. This lack of agreement stems from the variability in the characteristics that a smart port can have and is influenced by a number of factors, including technological evolution, the diversity of stakeholders involved, location-specific strategies and policies, geographical particularities, and the absence of global standards [9]. These factors contribute to the lack of a uniform and standardized definition of smart ports.

With technological advancement, the evolution of the port industry has led to the adoption of the fourth and fifth generations. Unlike the Industry 4.0 era, Industry 5.0 not only focuses on technological aspects but also actively seeks solutions that address social and environmental concerns. In this new industrial paradigm, ports are conceived as collaborative systems, where all logistics actors work together to enhance competitiveness [10,11].

Industry 5.0 is characterized by a holistic vision that embraces hyper-connectivity between technological, social, environmental, and economic aspects [12,13]. This innovative perspective considers key elements such as regulatory frameworks, governance, social tensions, environmental crises, the democratization of knowledge, and the promotion of sustainable innovation in the ecosystem [13,14]. This holistic approach makes a significant difference by addressing not only technological advances but also the regulatory, social, and environmental aspects that influence the dynamics of Industry 5.0.

Smart ports must imperatively integrate digital solutions into their strategies and goals that must prioritize customer satisfaction through efficient and effective operational and logistical planning [15]. It is possible to use Blockchain in the port logistics chain as it is possible to record, process, and track the data of each transaction transparently and reliably in real-time in a decentralized system that has a high level of security and fosters collaboration between actors with smart contracts [16].

The integration of digital solutions into the strategies and objectives of smart ports is essential in ensuring customer satisfaction through efficient and effective operations and logistics [15]. The feasibility of implementing Blockchain in the port logistics chain is evidenced by the digital platforms developed, such as TradeLens PM Maersk and IBM (2018), the Port of Singapore (2018), the Port of Hamburg (2018), the Port of Antwerp (2017 and 2018), and the Port of Rotterdam (2018) [17–19]. This technology facilitates the transparent and reliable recording, processing, and tracking of individual transaction data in real-time [16].

Operating in a decentralized system, blockchain provides robust security and promotes effective collaboration between the various actors in the port environment through smart contracts [16]. This integration not only boosts operational efficiency but also provides reliable data for the secure and effective management of transactions under Industry 5.0 in ports [20].

Problem Definition

Chile's extensive coastline and strategic location make its ports crucial hubs for international trade. Chile boasts major ports like San Antonio, Valparaíso, Antofagasta, Iquique, and Puerto Angamos, which handle diverse cargo, including containers, bulk commodities, and petroleum products. Growth in Chile's port sector is propelled by increased international trade, particularly in mining and agriculture, as well as significant investments in port infrastructure.

Revenue generation in Chilean ports is derived from handling fees, storage charges, vessel services, and ancillary services such as warehousing and logistics. The revenue streams are contingent upon factors such as cargo type, port infrastructure, offered services, and market demand. The Chilean government plays a regulatory and promotional role in the port sector, incentivizing investment through public-private partnerships (PPPs) and concession agreements to enhance port efficiency.

The port sector serves as a vital component of Chile's economy, facilitating trade, providing support to various industries, and creating job opportunities. Ports act as conduits, connecting Chilean exporters and importers with global markets.

In this context, Blockchain technology offers significant potential for revolutionizing supply chain management (SCM) within Chilean ports. Blockchain's distributed ledger ensures transparent and tamper-proof recording of supply chain data, providing a single source of truth in an environment where trust and transparency are paramount. By enabling seamless collaboration among stakeholders in port SCM, Blockchain facilitates real-time information exchange, leading to smoother operations and faster decision-making processes.

Efficient data management is a cornerstone of Industry 5.0, and Blockchain offers a secure means of managing supply chain data, encompassing documentation, transactions, and data from Internet of Things (IoT) sensors. By eliminating data silos and ensuring data integrity, Blockchain supports the goals of Industry 5.0, which emphasize automation and digitization.

Furthermore, Blockchain-based smart contracts automate compliance within the port SCM ecosystem. These smart contracts execute predefined actions based on specified conditions, streamlining processes such as customs clearance, compliance checks, and payments.

In addition to efficiency gains, Blockchain enhances resilience and security in the face of cybersecurity threats and supply chain disruptions. Its decentralized nature reduces the risk of cyberattacks and data breaches, while cryptographic algorithms safeguard supply chain data from unauthorized access or tampering.

Moreover, Blockchain facilitates traceability by recording each transaction or event in the supply chain, providing visibility that aids in tracking goods and ensuring quality control, recalls, and compliance audits. Overall, the adoption of Blockchain technology holds significant promise for transforming Chile's port sector into a more efficient, secure, and transparent ecosystem.

1.1. Research Gap of the Study

The existing research gap in integrating blockchain in maritime port supply chain management within Industry 5.0 might stem from the insufficient number of comprehensive studies that address the socio-economic and environmental ramifications of blockchain implementation. As interest in blockchain implementation continues to grow, it is imperative to examine its alignment with the principles of Industry 5.0, which highlight the importance of human-machine collaboration, sustainability, and societal well-being.

To be more precise, research could explore the investigation of:

Socio-economic Implications: What are the effects on employment patterns, labor dynamics, and income distribution among port workers and stakeholders resulting from the integration of blockchain technology in maritime port supply chains within the framework of Industry 5.0? Are there any prospects for enhancing the skills and knowledge of the workforce to meet the requirements of a digitalized supply chain?

Environmental Sustainability: What are the environmental consequences associated with the integration of blockchain technology in maritime port operations? Does the implementation of blockchain technology contribute to the reduction of carbon emissions, optimization of resource utilization, and promotion of sustainable practices in port ecosystems? In what ways can blockchain technology be utilized to improve transparency and accountability in environmental management?

Ethical and Governance Considerations: What are the ethical implications associated with the integration of blockchain technology in maritime port supply chains, specifically regarding data privacy, security, and ownership? What strategies can be implemented to design blockchain governance models that uphold fairness, transparency, and inclusivity in decision-making processes, in accordance with the principles of Industry 5.0?

The perception of blockchain technology in maritime supply chain management by different stakeholders, such as port authorities, shipping companies, local communities, and regulatory bodies, and its impact on stakeholder engagement and community will be explored. What social and cultural challenges may arise during the implementation of blockchain solutions, and how can they be effectively addressed to promote increased acceptance and collaboration?

Investigating these research gaps would yield valuable insights into the comprehensive ramifications of incorporating blockchain technology in the management of maritime port supply chains within the framework of Industry 5.0. It would enhance our comprehension of the socio-economic, environmental, and ethical aspects of digital transformation in maritime logistics while promoting the establishment of more inclusive and sustainable supply chain practices.

1.2. Contribution of the Study

This research provides theoretical and practical insights into applying blockchain technology (BT) in supply chain management (SCM) for Industry 5.0 in Chile's maritime sector.

The incorporation of Blockchain technology in the management of supply chains within maritime ports under the context of Industry 5.0 is significant due to its utilization of sophisticated decision-making methodologies like the fuzzy Logarithm Methodology of Additive Weights (LMAW) and Double Normalization-based Multiple Aggregation Methods (DNMA). Allow me to provide you with a comprehensive analysis of its contributions.

The integration of LMAW and DNMA within the context of Blockchain technology results in an enhanced decision-making framework. This framework effectively tackles the uncertainties and complexities linked to the management of maritime port supply chains, enabling decision-makers to make well-informed and efficient choices in optimizing port operations.

The Logarithm Methodology of Additive Weights (LMAW) addresses the challenges of vagueness and uncertainty, enabling decision-makers to effectively manage the inherent imprecise information in supply chain management. This holds particular relevance within the context of Industry 5.0, as the collaboration between humans and machines necessitates decision-making processes that can adapt to a diverse array of inputs and variables.

The utilization of Double Normalization-based Multiple Aggregation Methods (DNMA) enables the aggregation of various criteria and preferences from multiple stakeholders engaged in maritime port operations. This guarantees that decisions are executed in a just, transparent, and uniform fashion, in accordance with the principles of inclusivity and collaboration in Industry 5.0.

The strategic application of Blockchain can be achieved through the integration of LMAW and DNMA with Blockchain technology, allowing for effective management of maritime port supply chains. This facilitates the prioritization and ranking of crucial factors that impact the adoption of Blockchain, including transaction security, supply chain practices, and risk management, resulting in more focused and efficient implementation strategies.

Theoretical and Practical Contributions: The approach makes theoretical contributions through the development of a hybrid model that integrates LMAW and DNMA, thus enhancing the methodological toolkit for decision-making in Industry 5.0 contexts. Furthermore, the practical implementation of this technology facilitates the strategic incorporation of Blockchain in the field of maritime logistics, in accordance with the principles of Industry 5.0. This, in turn, leads to enhancements in the efficiency, transparency, and sustainability of supply chain operations.

Overall, the integration of Blockchain in Maritime Port Supply Chain Management using LMAW and DNMA represents a significant advancement in decision-making methodologies within the context of Industry 5.0. By leveraging these techniques, stakeholders can navigate the complexities of modern supply chains more effectively, fostering greater collaboration, innovation, and resilience in maritime port operations.

In this research, the key questions proposed are:

1. What are the primary barriers to implementing blockchain technology in the management of supply chains within an uncertainty-characterized environment?
2. How is multi-criteria decision-making utilized to prioritize the barriers impeding blockchain technology adoption in supply chain management?
3. What maritime line is most suitable for implementing blockchain technology?

This study is divided into six sections. The introduction summarizes the research gap, contribution, questions, and literature review. Section 2 includes the background of the port system and a literature review. Section 3 explains the research methodology, including the methods literature, research procedure, and screening process for factors. Section 4 presents the application's results in a real port case in Chile. Section 5 discusses the technical and strategic challenges and the contributions of review papers. Section 6 provides the research conclusions.

2. Background

2.1. Description of the Port System

As depicted in Figure 1, the Chilean port ecosystem is a complex network coordinated by the Port Administrator, who interacts with various public and private stakeholders, making strategic, tactical, and operational decisions based on their individual objectives [1]. These stakeholders are integral to the export and import logistics chains. Private companies offer services related to the management of port facilities, including loading and unloading goods, storage and inventory management, intermodal transportation, and logistical coordination. They also provide vessel maintenance and repair, equipment provision, and other specialized services tailored to maritime operations. These companies play a key role in managing supply chain efficiency and ensuring the timely delivery of goods.

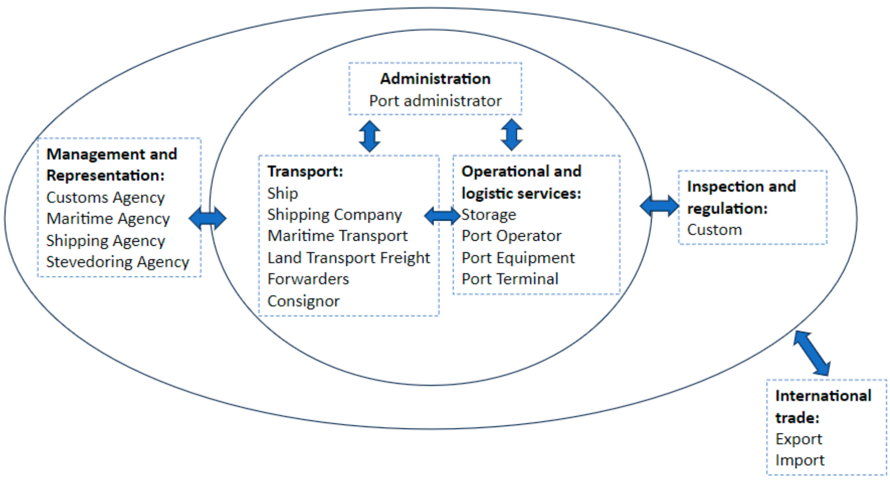

Figure 1. Port operational and logistical ecosystem.

Meanwhile, state organizations contribute by providing services overseeing port security and customs control, which are important for maintaining the integrity of international trade. They ensure compliance with national and international regulations, enforce security measures, and facilitate the smooth clearance of goods through customs. Furthermore, technological advancements and the digitalization of port operations are increasingly being adopted to enhance efficiency, reduce environmental impact, and improve overall service quality in the Chilean port system.

2.2. Data System

Efficient cargo documentation management is crucial for operational and administrative efficiency in export-import documentation. Port administrators face challenges in processing diverse administrative tasks, including vehicle and cargo control, environmental supervision, port security, customs documentation, and perishable goods handling [16].

Chilean public ports are regulated under Law 19.542 (1997), focusing on modernization and efficient regulation. Increasing global competitive pressures require enhanced operational efficiency and the adoption of disruptive technologies for advanced process automation and information systems. Strategic management should consider port-city relations and contemporary labor standards [15].

Chilean ports currently operate individual digital systems without coordination in export and import logistics chains. Technological development is classified as Industry 3.0 with characteristics of industry 4.0 due to a lack of investment in automation and cyber technological assets [1]. There is also a lack of human capital and knowledge and skills to manage projects with disruptive technologies.

The National Port Policy 2023 highlights the need for integrated systems like the Port Community System (PCS) to achieve strategic plans and become competitive ports with traceable data. Efforts are being made to integrate the PCS into maritime processes using the Maritime Single Window (VUMAR) and the Foreign Trade Single Window (SICEX). However, integrating disruptive technologies is challenging without a digital transformation plan for the logistics-port system.

Figure 2 illustrates the data and information flows in port management, emphasizing the importance of collaboration among private entities and public organizations. This coordination is crucial for efficient information management and adherence to security standards.

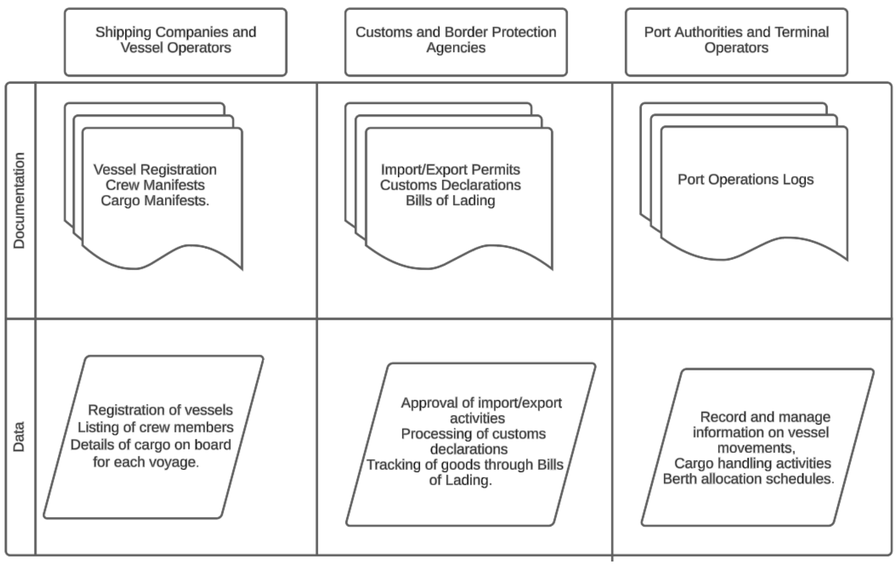

Figure 2. Information flow of the port system.

To enhance the efficiency of document management and cargo flow in Chilean ports, it is imperative to have information and communication processes that facilitate cost-effective, well-informed, collaborative, integrated, secure, and timely decision-making and reduce uncertainties inherent in the port system. Such uncertainties include time losses upon ship arrival, truck coordination, and other related issues. Reliable and efficient services are needed to provide advanced information on cargo traceability, thereby meeting client expectations while generating lower CO_2 emissions.

2.3. Literature Review

2.3.1. Challenges and Barriers of Blockchain in Maritime Port

In port management, blockchain technology offers significant enhancements in cargo tracking and administrative efficiency but faces implementation hurdles such as stakeholder reluctance, technological complexity, and the need for cross-sector collaboration [21–23]. While blockchain standardizes maritime documentation and ensures real-time data access, challenges remain in data traceability and establishing governance models [24,25].

Knowledge gaps, stakeholder resistance, and the need for innovative business models hinder the potential of blockchain in South Africa's KwaZulu-Natal province [26]. Successful implementation requires comprehensive strategies, risk management, and adherence to global standards [23].

In smart ports, blockchain aligns with goals of improved performance and environmental responsibility, yet its connection to Industry 4.0 and 5.0 involves overcoming challenges in automation and collaboration [2,27,28]. Digital technologies like blockchain contribute to environmental performance but face barriers such as technological complexity, regulatory hurdles, and cross-sector collaboration needs [21,22,25,29].

Blockchain is increasingly recognized as a pivotal solution for enhancing traceability in supply chain management (SCM) and fostering secure, reliable relationships not only between organizations and their suppliers but throughout the entire supply chain [30]. Key concerns such as trust, privacy, stakeholder support, scalability, data authentication, and supply chain risk management [23,26] are central to its adoption. Effectively addressing legal, operational, and technological challenges is crucial for integrating blockchain into maritime logistics, ensuring a more transparent, efficient, and secure global trade environment [16].

Addressing the lack of blockchain expertise and developing security protocols and risk assessments is crucial for enhancing scalability and performance in the maritime supply chain [24,31]. Promoting blockchain awareness, education, and standardization is key to overcoming resistance to change and ensuring economic viability [17,32,33].

Efficient information management through blockchain in port operations requires stakeholder participation and commitment to continual improvement [21,22]. Exploring blockchain's potential in port logistics involves deploying permissioned architectures and conducting SWOT analysis for operational clarity and compliance with global standards [24,25,34].

Advancing blockchain in maritime supply chains entails identifying stakeholders, addressing resistance to change, and tackling the lack of government regulations in international trade [26], alongside developing robust security and privacy protocols [2]. The ultimate goal is a blockchain-based maritime supply chain system enhancing efficiency, cost-effectiveness, and environmental sustainability, focusing on streamlining container turnover and the global trade process [30].

On the other hand, the reference model highlights the socio-technological aspects, emphasizing not only cybernetic advancements but also the integratioan of fundamental cultural components for effectively managing corporate innovations. In this context, it is necessary to analyze the effects of these technologies on workers and the communities where the companies are present. Aspects such as reducing unemployment, labor well-being, respect for human dignity, equality, privacy, and autonomy gain significant relevance, among others [12,35].

2.3.2. Multi-Criteria Decision-Making Methods in Blockchain-Operated Port Systems

The research explores the domain of maritime simulators and the decision-making process in port logistics, emphasizing the utilization of Bayesian BWM-PROMETHEE and various Multi-Criteria Decision Making (MCDM) techniques like Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOP-

SIS), and Preference Ranking Organization System Method for Enrichment Evaluation (PROMETHEE) [36]. These methods elevate the functionalities of the simulators and refine the decision-making regarding personnel management, particularly in the assessment of job attitudes, performance, and work ability. Nevertheless, they encounter obstacles such as the technical limitations of simulators, cost factors, and potential biases in MCDM methods, which affect the effective implementation of performance criteria in port operations. The authors propose future studies to concentrate on developing hybrid training modules for maritime simulators and examining diverse MCDMs and hybrid models to enhance personnel assessment in maritime logistics.

Moreover, the research investigates decision-making techniques in maritime practices through the utilization of methods such as Evaluation of Mixed data (EVAMIX), Novel Approach to Imprecise Assessment and Decision Environments (NAIADE), Analytic Network Process-Benefits, Opportunities, Costs and Risks (ANP-BOCR), TOPSIS, Failure Mode and Effect Analysis (FMEA), Decision Making Trial and Evaluation Laboratory (DEMATEL), and PROMETHEE [37–43]. These methods are employed in various contexts, ranging from sustainable transformations in port cities to sustainability assessments in Mediterranean ports. While providing comprehensive assessments, conflict resolution, and efficiency in team settings, these techniques encounter challenges such as biases in selecting indicators and context-specific limitations. Future research is recommended to focus on applying and evaluating MCDA methods for sustainable strategies in port cities, enhancing decision-making for port sustainability, and establishing frameworks for measuring sustainability in port city transformations.

3. Materials and Methods

3.1. Methods

In this research, the multiple-criteria decision analysis (MCDA) method is employed, offering several alternatives from which one must be chosen. Although there are many MCDA methods in the literature, the Logarithm Method of Additive Weights (LMAW) was chosen because it is more robust when dealing with both large and small numbers in a decision versus criteria table (see Table 1). Another feature of this method is that it is less sensitive to an increase in alternatives. Therefore, if other alternatives are to be added to the decision after the analysis is completed, this method maintains coherence with the previously selected decision [44].

Table 1. Matrix X of experts, with $1 \leq e \leq k$.

Alternatives	C_1:*Criterion* **1**	C_2:*Criterion* **2**	...	C_n:*Criterion n*
A_1 : *alternative* 1	δ^e_{11}	δ^e_{12}	...	δ^e_{1n}
...	...	...	...	...
A_m : *alternative m*	δ^e_{m1}	δ^e_{m1}		δ^e_{mn}

3.1.1. Logarithm Method of Additive Weights (LMAW)

The algorithm requires the following stages and steps.

Stage 1. Construction of the Aggregated X Matrix

There are m alternatives considered, denoted by the letter A and subscripts, in the following manner $A = \{A_1, \ldots, A_m\}$, which are compared using n criteria, named with the letter C and subscripts, in the following way $C = \{C_1, \ldots, C_n\}$. The matrix X of the expert has the table structure presented in Table 1. The elements of each cell are named with the letter delta. There are k experts:

$$E = \{E_1, \ldots, E_k\} \tag{1}$$

From each of these tables corresponding to different experts, the following expression is applied to construct each cell of the unified matrix that synthesizes the opinion of all the experts. This matrix will be called Υ.

$$\delta_{ij} = \left(\frac{1}{k(k-1)} \sum_{x=1}^{k} \left(\delta_{ij}^{x}\right)^{p} \sum_{\substack{y=1 \\ y \neq x}}^{k} \left(\delta_{ij}^{y}\right)^{q} \right)^{\frac{1}{p+q}} \tag{2}$$

In this research, δ_{ij} denotes the average values calculated using the Bonferroni aggregator [44] for constructing the aggregated X matrix. This function effectively merges information on an ordinal scale to yield a comprehensive summary representative of various expert opinions. An important property of this aggregation operator is its monotonic increase in output relative to the increase in input values. The concept of monotonicity, initially introduced in a weak form [45,46], evolved into the concept of directional monotonicity. Subsequently, the idea of pre-aggregation functions was formulated [47], providing a systematic approach to aggregation. Further exploration of these functions led to the development of a novel pre-aggregation method [48]. Among the prominent aggregation functions in the literature is the Choquet integral [49], which employs a fuzzy measure for data fusion. The study utilizes the Bonferroni mean operator (BM) [50], an effective fusion function capable of modeling interconnections among data inputs. The BM operator, as described by [51], combines the features of both averaging and aggregating operators. This research, for simplicity, opts for the classical Bonferroni operator.

Stage 2: Normalization of the Aggregated X Table

In order to achieve consistency, it is necessary to normalize the values of each criterion. This step plays a vital role in guaranteeing the comparability of criteria with varying units or magnitudes. The term $\delta_j^{+} = \{\delta_{ij}\}$ is defined as the maximum criterion value, while $\delta_j^{-} = \{\delta_{ij}\}$ denotes the criterion fulfilling the minimum requirement. In this context, δ_{ij} denotes the values obtained in the aggregated table (refer to Table 1), which are calculated based on the defined expression.

$$\delta_{ij} = \begin{cases} \frac{\delta_{ij}+\delta_j^{+}}{\delta_j^{+}} & if\ the\ criterion\ j\ is\ of\ max \\ \\ \frac{\delta_{ij}+\delta_j^{-}}{\delta_{ij}} & if\ the\ criterion\ j\ is\ of\ min \end{cases} \tag{3}$$

Stage 3: Determining the Weights of Decision Criteria

Allocate weights to each criterion based on their significance in the decision-making process. The determination of these weights can be achieved either through a subjective assessment conducted by decision-makers or by employing objective measures. Experts from set E prioritize criteria from set C using predefined linguistic scale values, assigning higher values to criteria of greater importance. For instance, a possible scale might range from 'strongly disagree' valued at 1 to 'strongly agree' with higher values. The more significant criteria should have higher numerical values. Consequently, for expert e, a priority vector is obtained, $P^e = \left(\gamma_{C1}^{e}, \gamma_{C2}^{e}, \ldots, \gamma_{Cn}^{e}\right)$, where γ_{Cn}^{e} is the linguistic scale value assigned by expert e, with $1 \leq e \leq k$, for criterion C_j with $1 \leq j \leq n$. The method then divides into three steps.

Step 1. For each expert e, with $1 \leq e \leq k$, the minimum priority value is defined and is referred to as the anti-ideal point.

$$\gamma_{AIP} = \frac{\min\{\gamma_{C1}^{e}, \ldots\ldots, \gamma_{Cn}^{e}\}}{s} \tag{4}$$

where s represents the smallest integer greater than the logarithm base used in step 2.

Step 2. Involves normalizing the prioritization values from each expert by dividing these by the anti-ideal point γ_{AIP} as follows:

$$\eta_j^e = \frac{\gamma_{c_j}^e}{\gamma_{AIP}} \ldots = 1, \ldots, n \quad \ldots e = 1, \ldots, k \tag{5}$$

Subsequently, the priority vector of expert e is obtained, relative to the anti-ideal value.

Step 3. The weight vector for the decision criteria of expert e is determined using the logarithmic value formula, which stabilizes the numerical values. The logarithmic function is utilized to aggregate the normalized values of all criteria. This function integrates the weighted values of each criterion to generate a comprehensive score for each alternative.

$$w_j^e = \frac{\left(\eta_j^e\right)}{b^e} \quad , \quad j = 1, \ldots, n \quad , \quad e = 1, \ldots, k \tag{6}$$

where η_j^e is derived using the expression from step 2 and the following equation:

$$w_j^e = \frac{\log_A\left(\eta_j^e\right)}{\log_A(b^e)} \quad , \quad j = 1, \ldots, n \quad , e = 1, \ldots, k \tag{7}$$

The Bonferroni aggregator is applied, resulting in:

$$w_j = \left(\frac{1}{k(k-1)} \sum_{x=1}^{k} \left({w_j}^x\right)^p \sum_{\substack{y=1 \\ x \neq y}}^{k} \left({w_j}^y\right)^q \right)^{\frac{1}{p+q}} \tag{8}$$

where p, $q \geq 0$ are the stabilization parameters of the Bonferroni aggregator, and ${w_j}^e$ represents the weighting coefficients of expert e.

Step 4: Calculation of the Weights for Matrix Y. It is requested that you rank the alternatives based on their aggregated scores. The alternative with the highest score is considered to be the most favorable or preferred choice.

The elements of matrix Y are determined by applying the following expression:

$$\rho_{ij} = \frac{2\sigma_{ij}^{w_j}}{\left(2 - \sigma_{ij}\right)^{w_j} + \sigma_{ij}^{w_j}} \tag{9}$$

with

$$\sigma_{ij} = \frac{\ln \delta_{ij}}{\ln \prod_{i=1}^{m} \delta_{ij}} \tag{10}$$

in which δ_{ij} represents the cells ij of the matrix Y.

Step 5. Calculate the final ranking index of alternatives Q_i.

$$Q_i = \sum_{j=1}^{n} \rho_{ij} \quad , \quad i = 1, \ldots, m \tag{11}$$

This ranking represents an initial list refined using the double normalization-based multiple aggregation (DNMA) method.

3.1.2. Double Normalization-Based Multiple Aggregation (DNMA) Method

The process of normalization aims to standardize the values of each criterion within each alternative, ensuring consistency across a single scale. The significance of this step cannot be overstated as it is essential for ensuring comparability among different criteria. The DNMA method is considered as an innovative approach for enumerating alternatives [52]. It combines two unique normalization techniques—linear and vector-based approaches—and integrates three distinct joining functions: full compensation (CCM), incomplete compensation (UCM), and incomplete compensator (ICM). To implement this method, Equation (12) is utilized for linear x_{ij}^{1N} normalization of decision matrix elements, while Equation (13) is applied for vector x_{ij}^{2N} normalization.

$$\tilde{x}_{ij}^{1N} = 1 - \frac{\left|x^{ij} - r_j\right|}{max\left\{\underset{i}{max}\ \ x^{ij}, r_j\right\} - min\left\{\underset{i}{min}\ x^{ij}, r_j\right\}} \tag{12}$$

$$\tilde{x}_{ij}^{2N} = 1 - \frac{\left|x^{ij} - r_j\right|}{\sqrt{\sum_{i=1}^{m}\left(x^{ij}\right)^2 + \left(r_j\right)^2}} \tag{13}$$

The value r_j will be established as the target for both benefit and cost criteria, represented by the criterion c_j. For the benefit criterion, the objective is to maximize each x^{ij}, while for the cost criterion, the aim is to minimize each x^{ij}.

Determining the Weights of Criteria

In the initial stage of analysis, calculate the standard deviation for each criterion, where "m" represents the total number of alternatives considered. Employ double normalization to ensure that the aggregated scores of each criterion are standardized and can be compared. The normalization step is performed twice, once for each level of aggregation.

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m}\left(\underset{i}{max}\frac{x^{ij}}{ij} - \frac{1}{m}\sum_{i=1}^{m}\left(\frac{x^{ij}}{\max\ x^{ij}}\right)\right)^2}{m}} \tag{14}$$

Equation (15) is applied to normalize the calculated standard deviation values associated with the specified criteria.

$$w_j^{\sigma} = \frac{\sigma_j}{\sum_{i=1}^{n}\sigma_j} \tag{15}$$

Ultimately, a specific equation is utilized to accurately adjust the weights in the analysis.

$$\tilde{w}_j = \frac{\sqrt{w_j^{\sigma}}.w_j}{\sum_{i=1}^{n}\sqrt{w_j^{\sigma}}.w_j} \tag{16}$$

Determining Aggregation Models through Calculation

The evaluation of each alternative involves distinct calculations using three specific aggregation functions: CCM, UCM, and ICM. CCM is calculated:

$$u_1(a_i) = \sum_{j=1}^{n}\frac{\tilde{w}_j.\tilde{x}_{ij}^{1N}}{\underset{i}{\max}\tilde{x}^{ij}} \tag{17}$$

The calculation of the Uncompensatory Model (UCM) involves the use of:

$$u_2(a_i) = \underset{j}{\max} w_j\left(\frac{1 - \tilde{x}_{ij}^{1N}}{\underset{i}{\max}\tilde{x}^{1j}}\right) \tag{18}$$

The Incomplete Compensatory Model (ICM) is based on the equation:

$$u_3(a_i) = \prod_{j=1}^{n} \left(\frac{\overset{\sim 2N}{x_{ij}}}{\max\limits_i \overset{\sim 2j}{x}} \right)^{\widetilde{w}_j} \tag{19}$$

The Integration of Values Related to Usefulness

The utility functions that have been calculated are incorporated with Equation (20) through the utilization of the Euclidean distance principle to rank the alternatives according to their doubly normalized scores. The option with the highest doubly normalized score is regarded as the most favorable or preferred alternative.

$$\begin{aligned} DN_i \quad &= w_1 \sqrt{\varphi \left(\frac{u_1(a_i)}{\max\limits_i \ (a_i)} \right)^2 + (1-\varphi) \left(\frac{m - r_1(a_i) + 1}{m} \right)^2} \\ &- w_2 \sqrt{\varphi \left(\frac{u_2(a_i)}{\max\limits_i u_2(a_i)} \right)^2 + (1-\varphi) \left(\frac{r_2(a_i)}{m} \right)^2} \\ &+ w_3 \sqrt{\varphi \left(\frac{u_3(a_i)}{\max\limits_i u_3(a_i)} \right)^2 + (1-\varphi) \left(\frac{m - r_3(a_i) + 1}{m} \right)^2} \end{aligned} \tag{20}$$

Here, $r_1(a_i)$ and $r_3(a_i)$ are sequence numbers for a_i based on CCM and ICM functions, sorted in descending order for the highest value priority. Conversely, $r_2(a_i)$ represents the sequence for a_i according to UCM function, sorted in ascending order for the lowest value priority. The φ coefficient, with a suggested default value of 0.5, indicates the relative importance of subordinate utility values, within a $[0, 1]$ range. The weights w_1, w_2, w_3 represent the importance of CCM, UCM, and ICM functions, respectively, and $w_1 + w_2 + w_3 = 1$, determined by decision makers. Weight allocation depends on the decision maker's focus: w_1 for broader performance preference, w_2 for risk aversion, and w_3 for a balance of performance and risk. The alternatives are then ranked in descending order based on DN values, with the highest value indicating the best alternative. The method's processing steps are outlined in Figure 3.

3.2. Reason of Using These MCDA Methods

3.2.1. Fuzzy LMAW

The Fuzzy Logarithm Methodology of Additive Weights (LMAW) method offers several advantages:

Flexibility: LMAW allows for the integration of fuzzy logic, enabling a more flexible representation of decision-maker preferences. Fuzzy logic permits the modeling of imprecise or uncertain information, which can be especially valuable in decision-making scenarios where precise data may be lacking.

Scalability: The additive weights approach within LMAW makes it scalable and adaptable to different decision-making contexts. This scalability means that the method can be applied to a wide range of decision problems, from simple to complex, without significant modifications.

Simplicity: Despite its flexibility, LMAW remains relatively straightforward to implement and understand. This simplicity makes it accessible to decision-makers who may not have specialized training in mathematical modeling or optimization techniques.

Transparency: LMAW provides transparency in decision-making by breaking down complex decisions into understandable components. This transparency can help stakeholders understand how decisions are made and facilitate buy-in and consensus-building.

Integration of Multiple Criteria: LMAW allows decision-makers to incorporate multiple criteria or objectives into the decision-making process. By assigning weights to each criterion, decision-makers can prioritize different factors according to their importance, leading to more balanced and informed decisions.

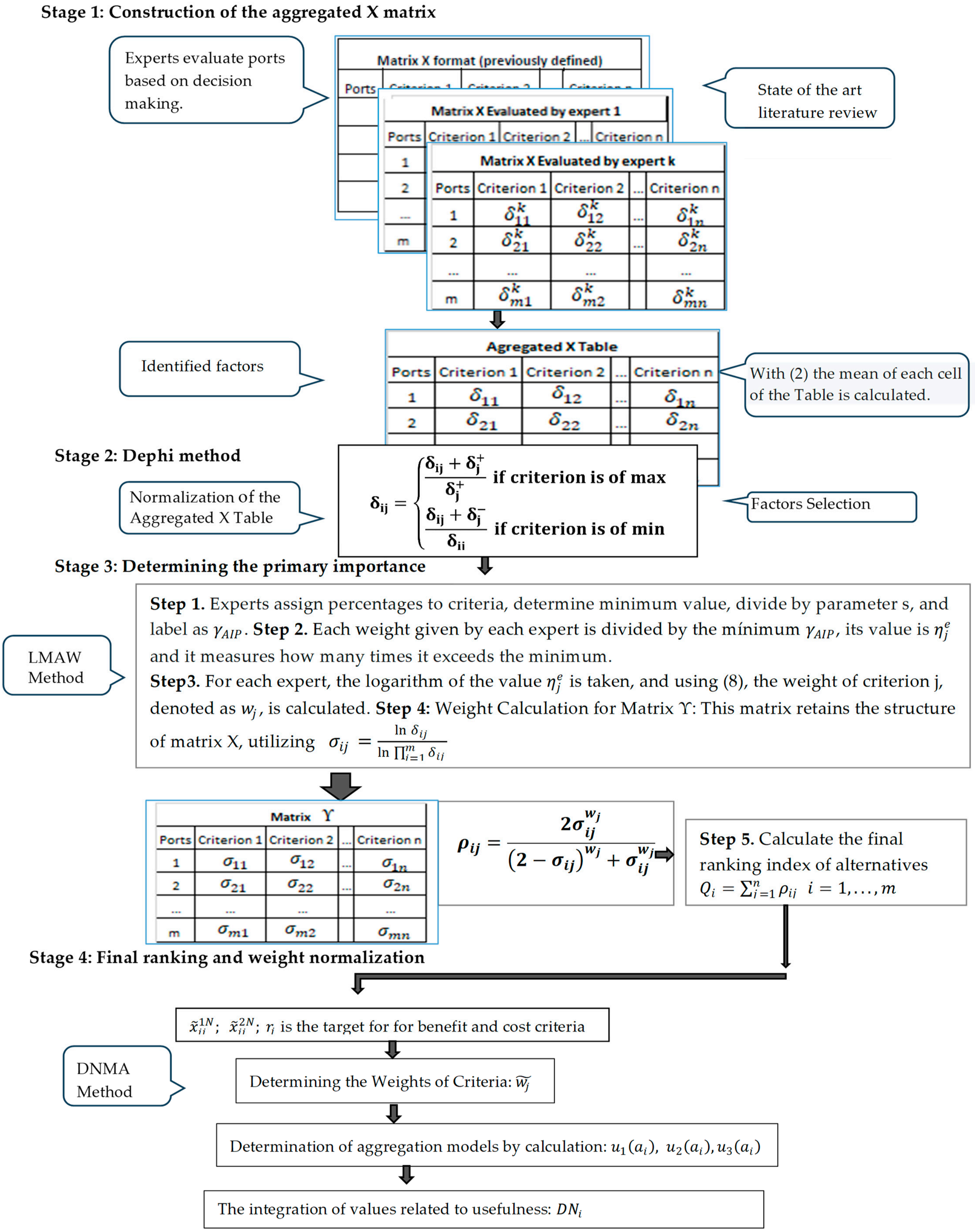

Figure 3. Research methodology.

Adaptability to Uncertainty: The fuzzy logic component of LMAW enables the method to handle uncertainty and ambiguity in decision-making. By allowing for the representation of vague or subjective information, LMAW can generate robust decisions even in the presence of uncertainty.

Accounting for Subjectivity: LMAW acknowledges and accommodates the subjective nature of decision-making by allowing decision-makers to express their preferences in a flexible and intuitive way. This subjectivity is particularly relevant in situations where decision outcomes depend on individual judgments or opinions.

Overall, the advantages of the Fuzzy Logarithm Methodology of Additive Weights (LMAW) method include its flexibility, scalability, simplicity, transparency, integration of multiple criteria, adaptability to uncertainty, and ability to account for subjectivity, making it a versatile tool for decision support in various contexts.

3.2.2. DNMA Method

The method known as Double Normalization-based Multiple Aggregation Methods (DNMA) presents various benefits:

Robustness: DNMA offers a resilient methodology for decision-making through the implementation of double normalization techniques. The process of normalization aids in the standardization of data across various scales, guaranteeing equal treatment of all criteria in the decision-making procedure. The strength of this robustness minimizes the potential for bias and guarantees that decisions are founded on a fair evaluation of all pertinent factors.

Flexibility: DNMA provides flexibility in the aggregation of multiple criteria, enabling decision-makers to utilize a range of aggregation functions. This flexibility allows decision-makers to customize the method according to the unique attributes of their decision problem, resulting in outcomes that are more precise and significant.

Enhanced transparency: DNMA achieves enhanced transparency through the double normalization process, rendering the decision-making process explicit and comprehensible. By utilizing well-established methodologies, DNMA facilitates the standardization of data and the aggregation of criteria, thereby offering decision-makers clear insights into the contribution of individual criteria towards overarching decisions.

Integration of multiple criteria: DNMA enables the integration of multiple criteria into the decision-making process, offering a systematic framework for aggregating various sources of information. Decision-makers can integrate a diverse range of criteria, including cost, quality, and risk, resulting in more comprehensive and well-rounded decisions.

Sensitivity analysis: DNMA facilitates the evaluation of the influence of modifications in criteria weights or aggregation functions on decision outcomes. This functionality aids decision-makers in comprehending the resilience of their decisions and pinpointing areas that may require adjustments to enhance decision quality.

Consistency: DNMA fosters consistency by offering a systematic method for combining various criteria in decision-making. Decision-makers can ensure consistent decision-making across various contexts by adhering to standardized procedures for normalization and aggregation.

Adaptability: The DNMA framework demonstrates adaptability in addressing complex decision problems involving multiple criteria and stakeholders. Utilizing robust normalization and aggregation techniques, DNMA is suitable for addressing a wide range of decision-making challenges, including resource allocation and project selection.

3.3. Relationship between Blockchain Technology, SCM in Port, and Industry 5.0

The implementation of technology in port supply chain management enables the creation of a transparent and traceable record for every stage of the cargo handling process. This guarantees that stakeholders possess immediate access to the tracking of goods, thereby minimizing the potential for fraud, theft, or counterfeiting. The utilization of blockchain-based systems can facilitate the digitization and automation of the documentation process within ports, resulting in a reduction of paperwork and administrative burdens. Through the utilization of blockchain technology, smart contracts have the capability to autonomously ensure adherence to regulations and contractual obligations, facilitating the efficiency of customs clearance and regulatory inspections. Moreover, the utilization of blockchain technology enables ports to enhance collaboration among a diverse range of stakeholders, such as shipping companies, freight forwarders, customs authorities, and port operators. The provision of shared access to a secure and decentralized ledger facilitates the seamless exchange and coordination of information, resulting in expedited turnaround times and diminished transit delays. The incorporation of blockchain technology into port supply chain management is in line with the tenets of Industry 5.0, as it facilitates collaboration and customization between humans and machines. One example would be the utilization of blockchain-based platforms, which can provide port workers with real-time data and analytics, empowering them to make well-informed decisions and effectively adapt to evolving operational demands.

4. Results

4.1. Delphi Method

Industry 5.0 literature, transcending various sectors, envisions a future where technology from Industry 4.0 is harmoniously integrated with human values. Unlike its predecessor, which is technology-centric, Industry 5.0 adopts a human-centric and holistic approach, focusing on addressing wider societal, environmental, and energy challenges. It emphasizes the role of humans not just as technology users but as vital players in addressing global issues, fostering personalized product creation through human-robot interaction. In Industry 5.0, the regulatory landscape is expansive, addressing the need for voluntary regulations to aid data sharing in Industry 4.0 and new regulations to guide resources and work practices in Industry 5.0. This shift presents challenges in regulation, cross-sector influence, and the cultural impact on investments and consumer behaviors. The present study utilizes the Delphi method, a technique primarily used in research and economics for consensus-building through expert opinions. Originally developed in the 1950s for military purposes, this method involves gathering insights from experts via questionnaires.

The study, detailed in Table 2, used the Delphi method to collect important data through the participation of executives and service providers from the ports of Valparaíso, San Antonio, and Coquimbo. The experts were chosen for their knowledge in operational and business management within port logistics. The selection criteria covered their current roles, their experience in the sector, and their contributions to industry practices.

The selection of parameters in the Logarithm Methodology of Additive Weights (LMAW) or Double Normalization-based Multiple Aggregation Methods (DNMA) can significantly influence the results of the decision-making process. The assigned weights for each criterion indicate their significance in the decision-making process. If these weights are inaccurately assigned, either by overemphasizing or underemphasizing particular criteria, the overall outcome can be biased toward or against specific alternatives. The choice between subjective evaluations made by decision-makers and objective measures, such as data analysis or expert opinions, can impact the fairness and credibility of the weighting procedure. Subjective weights have the potential to introduce bias, while objective weights may overlook nuanced qualitative factors. The selection of a normalization method can influence the relative significance of each criterion. Various normalization techniques, such as min-max normalization and z-score normalization, can result in diverse interpretations of criterion values, thereby impacting the overall outcomes. The normalization range, which encompasses the minimum and maximum values, can impact the scaling of criterion values. Choosing an unsuitable range can lead to distorted comparisons between criteria and alternatives. The sensitivity of the method to variations in individual criteria can be influenced by the aggregation function used to combine criterion values. Alternatives can receive different overall scores depending on the choice of aggregation function, including linear aggregation, weighted aggregation, and exponential aggregation. In cases where the aggregation method incorporates the use of weightings for criteria, the selection of a specific weighting scheme (such as equal weighting, proportional weighting, or expert weighting) can significantly influence the ultimate result by giving more prominence to certain criteria compared to others. The convergence and stability of the method can be influenced by the number of normalization iterations conducted in DNMA. Inadequate iterations can result in imprecise comparisons, while excessive iterations can introduce computational inefficiencies without substantial improvement in outcomes.

Table 2. Delphi results.

Factors	DM1	DM2	DM3	DM4	DM5	DM6	Average	Accept/Reject
Reduced paperwork & cost savings	*3*	*2*	*3*	*3*	*3*	*3*	2.83	R
Reduction in transaction time	*3*	*3*	*4*	*4*	*4*	*3*	3.50	R
Enhanced transaction security	*4*	*4*	*5*	*4*	*4*	*3*	4.00	A
Optimization in port operations	*4*	*4*	*4*	*4*	*4*	*3*	3.83	R
Sustainability promotion	*3*	*3*	*4*	*4*	*3*	*4*	3.50	R
Technological implementation cost	*3*	*3*	*3*	*4*	*4*	*3*	3.33	R
Regulatory compliance	*4*	*3*	*3*	*4*	*4*	*4*	3.67	R
Resistance to change	*2*	*3*	*4*	*3*	*4*	*4*	3.33	R
Technology challenge	*4*	*3*	*4*	*4*	*5*	*3*	3.83	R
Circular management	*2*	*2*	*5*	*3*	*2*	*4*	3.00	R
Good practices in the supply chain	*5*	*4*	*4*	*4*	*4*	*3*	4.00	A
Cyber-technological implementation	*2*	*3*	*4*	*4*	*5*	*3*	3.50	R
Collaborate and coordinate actors	*3*	*3*	*4*	*4*	*4*	*4*	3.67	R
Implement leadership strategies	*3*	*3*	*3*	*4*	*4*	*4*	3.50	R
Spend on technology assets	*3*	*3*	*4*	*3*	*5*	*4*	3.67	R
Risk Identification	*5*	*4*	*3*	*4*	*4*	*4*	4.00	A
Manage contingencies	*5*	*2*	*5*	*5*	*5*	*3*	4.17	A
Port infrastructure investment	*4*	*4*	*3*	*3*	*4*	*4*	3.67	R
Enhanced security	*5*	*4*	*4*	*4*	*4*	*3*	4.00	A
Ensure transparency of information	*4*	*3*	*4*	*4*	*4*	*4*	3.83	R
Staff technical competencies	*4*	*3*	*3*	*4*	*4*	*4*	3.67	R
Governance affects decision making	*4*	*3*	*3*	*4*	*4*	*4*	3.67	R

4.2. LMAW Analysis

Table 3 shows the linguistic variables that decision-makers assign to their answers to questions for the LMAW method.

Table 3. DMs response scale.

Linguistic Variables	Abbreviation	Prioritization
Absolutely Low	AL	1
Very Low	VL	1.5
Low	L	2
Medium	M	2.5
Equal	E	3
Medium High	MH	3.5
High	H	4
Very High	VH	4.5
Absolutely High	AH	5

4.2.1. LMAW Analysis

In Table 4, the decision matrix has been created, and in this research, the value of γ_{AIP} is set to 0.5 following Equations (4) and (5).

Table 4. Decision matrix.

KIND	1	1	−1	1	1
	Enhanced Transaction Security	**Good Practices in the Supply Chain**	**Risk Identification**	**Manage Contingencies**	**Enhanced Security**
Expert 1	H	AH	AH	AH	AH
Expert 2	H	H	H	L	H
Expert 3	AH	H	E	AH	H
Expert 4	H	H	H	AH	H

Next, the transition from fuzzy numbers to crisp numbers occurs. Then, the vector of weight coefficients is calculated, where W_{ij} represents the ith experts and jth criterion according to Equation (3).

Table 5 shows the aggregated fuzzy vectors and the final weights from Equation (4).

Table 5. Weight coefficients vector.

Weight Coefficients Vector	Enhanced Transaction Security	Good Practices in the Supply Chain	Risk Identification	Manage Contingencies	Enhanced Security
W_{1j}	0.184	0.204	0.204	0.204	0.204
W_{2j}	0.214	0.214	0.214	0.143	0.214
W_{3j}	0.218	0.197	0.170	0.218	0.197
W_{4j}	0.196	0.196	0.196	0.217	0.196

4.2.2. DNMA Analysis

In the first step, the initial matrix has been created as shown in Table 6.

Table 6. Initial matrix.

	1	**1**	**−1**	**1**	**1**
Weight	**0.2029**	**0.2027**	**0.1957**	**0.1946**	**0.2027**
	C1	C2	C3	C4	C5
Valparaiso	4	5	5	5	5
San Antonio	4	4	4	2	4
Coquimbo	4	4	3	5	4
Lirquen	3	3	4	3	3
MAX	4	5	5	5	5
MIN	3	3	3	2	3

The linear and vector normalization matrices were calculated according to Equation (5), followed by the calculation of the standard deviation using the criteria in Equation (6). This standard deviation was then normalized, resulting in adjustments to the weights as specified in Equation (8). Subsequently, the Complete Compensatory Model (CCM), Uncompensatory Model (NCM), and Incomplete Compensatory Model (ICM) were obtained. The final ranking of ports is shown in Table 7 (Equation (12)).

Table 7. Final ranking.

Port	**CCM**		**φ**	**UCM**		**φ**	**ICM**		**φ**	**Utility Values**		**Rank Order**
	u1(ai)	**Rank**	**0.5**	**u2(ai)**	**Rank**	**0.5**	**u3(ai)**	**Rank**	**0.5**			
Valparaiso	0.810	1	1.0000	0.189	2	0.631	0.951	2	0.879	0.927	0.927	1
San Antonio	0.456	3	0.5324	0.256	4	1.000	0.848	4	0.650	0.614	0.614	3
Coquimbo	0.807	2	0.8815	0.096	1	0.319	0.958	1	1.000	0.860	0.860	2
Lirquen	0.360	4	0.3605	0.192	3	0.751	0.928	3	0.771	0.522	0.522	4

4.3. Sensitive Analysis

In the final step, we are interested in understanding how changes in the amount affect the weights of fuzzy LMAW. In computing the model, we initially consider 0.5 for FLMAW. However, we now explore these factors from 0.1 to 1 to determine the tolerance for change. If the variation is significant, it indicates that the result is not reliable. Figure 4 illustrates the reliability among the weightings, showing that some of the weighting factors overlap with each other.

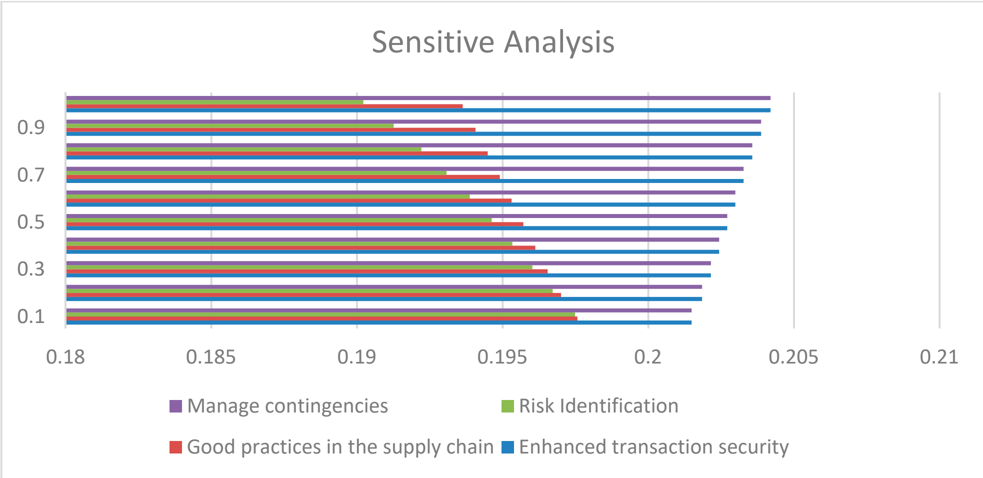

Figure 4. Sensitive analysis.

'Supply chain best practices' and 'improved transaction security' are omitted because the ports studied are still in the adoption phase of Industry 4.0 technologies and have not prioritized the high investment required to implement blockchain, a technology that enhances these practices and security. Currently, they are more focused on increasing levels of automation and digitization, without giving sufficient importance to the operational advantages offered by blockchain.

5. Discussion

5.1. Technical Aspects

In the search for the optimal integration of Blockchain technology within the SCM of Chilean ports, our study used the Fuzzy Logarithmic Methodology of Additive Weights (LMAW) and the Double Normalization-based Multiple Aggregation Methods (DNMA). These methods were instrumental in ranking and weighting various factors that influence the effective deployment of BT. The process was executed in phases:

- Factor Identification and Prioritization: Initially, 22 factors influencing port selection were identified using the Delphi method. Subsequently, five key factors were prioritized based on the opinions of decision-makers, using fuzzy LMAW for the initial rankings.
- Port ranking and strategic importance: Ports were then ranked using DNMA based on the weighted factors derived from fuzzy LMAW. The port of Valparaiso was found to be the highest priority, highlighting its strategic importance to Chile's MTS modernization efforts.

5.2. Strategic Challenges

To explore the primary characteristics influencing port operational strategies via technology, the strategic dimensions linked with blockchain and Industry 5.0 were scrutinized. This examination was carried out via an in-depth literature review in Section 2.3. The essential terms pinpointed in the literature are outlined in Table 8 and are categorized following the PESTA (Political, Economic, Social, Technological, and Environmental) framework, which underscores the macro-environmental factors impacting seaport operations.

Table 8 illustrates the keywords associated with blockchain integration in maritime port operations, highlighting the key strategic challenges within the context of Industry 5.0 and the PESTA macro-environment analysis. From a policy and legal perspective, the need to strengthen regulatory compliance and develop governance models that respond to digital advances, adapting legal frameworks to emerging technologies such as blockchain, is evident. Socially, resistance to change is a considerable barrier, which could be mitigated with proactive strategies that foster training, job security, and transparent communication, thus promoting an inclusive and adaptive environment. Environmentally, it is essential to drive sustainable practices in port operations, aligning these initiatives with global sustainability goals. Economically, it is crucial to balance the high costs of implementing blockchain with obtaining operational efficiencies that justify such investment. Technologically, challenges such as data management, systems integration, and security of digital transactions are highlighted, requiring a robust infrastructure and active and continuous participation of all stakeholders to ensure efficient integration and maximize the potential of blockchain.

Table 8. Strategic keywords.

Paper	Legal/Political	Social	Ambiental	Economic	Technological
[31]	New regulations; data privacy	Expert responses; worker resistance; job security.			Blockchain integration
[32]	Regulatory compliance.	Adaptation; stakeholder participation.		Data and information management rights distribution; operations and logistics services improvement.	Information systems adaptation; data distribution; Blockchain integration.
[21]	Regulatory compliance.	Stakeholder involvement.		Financial procedures; operational efficiency.	Blockchain, platform; cargo tracking; document workflow management; security in operations.
[22]	Legal changes; compliance with advanced industry standards.	New practices; workforce management.	Eco- friendly supply chain; reducing paper usage.	Supply chain efficiency; cost reduction in operations.	Blockchain integration of systems; smart supply chain networks; digitalization of documentation.
[17]	Legal adaptation; standardization.	Resistance to change; collaboration.		High costs	Blockchain integration; document flow management; financial processes; device connectivity; integration of systems; big data management.
[25]	Governance models; regulatory aspects.	Stakeholder collaboration.		Operational efficiency; improve logistic; transactional operations.	Systems; automation of transactional operations; Platforms; frameworks.
[33]	Legal conditions in digital processes.	Stakeholder coordination; community engagement.		Business networks; operational efficiency.	Smart contracts; Blockchain implementation; digitizing documentation; connectivity and data exchange.
[24]	Global standards; regulatory compliance.	Decision-makers at the operational level.	Reducing paper usage.	Transaction-related business challenges.	Document flow management; real-time data sharing; data traceability; interoperability among different actors.
[26]	Government regulations; customs authorities; privacy regulations.	Trust issues; limited understanding among stakeholders; adoption process.		Operational and logistic efficiency.	Blockchain; technological development in export and import logistics chains.
[30]	Governmental support.	Human capital; knowledge and experience; resistance to change.	Environmental impacts.	Efficiency; business models; global trade.	Decentralized platform; improve security; integration.

6. Conclusions

Today, companies are recognizing the transformative power of blockchain technology (BT) in supply chain management (SCM). By integrating BT, companies can effectively track goods and reduce the overall cost of goods. However, the implementation of BT in SCM involves multiple factors that need careful consideration and prioritization, as they significantly influence the success of its adoption. The maritime port sector, especially in Chile, plays a crucial role due to its high turnover rates. This study is aimed at a diverse audience including researchers, supply chain professionals, port operations specialists, blockchain experts, and decision scientists using multi-criteria decision-making (MCDM) methods in complex environments. With the advent of Industry 5.0, BT assumes a critical role. The objective of this research is to first identify and then prioritize the key factors that influence the implementation of BT in Chilean seaports using the LMAW method, followed by ranking the ports with the DNMA method to determine their readiness for BT implementation.

Enhanced Decision-Making: LMAW and DNMA present systematic approaches for decision-makers to appraise and prioritize alternatives considering various criteria. Within the context of SCM ports in Industry 5, where there is a high level of complexity and data volume, these methods provide systematic approaches to manage various factors that impact decision-making, such as cost efficiency, risk management, and security enhancement. These methodologies facilitate the recognition of vital elements that impact port performance and support well-informed decision-making to improve operational efficiency and competitiveness. The utilization of LMAW and DNMA permits port operators to evaluate and give priority to risk factors, allowing for proactive implementation of risk management strategies to mitigate potential disruptions and ensure the resilience of port operations.

The allocation of resources in a strategic manner is crucial for supply chain management (SCM) ports to effectively fulfill increasing demands while remaining cost-effective. The utilization of LMAW and DNMA aids in the prioritization of investment decisions, such as infrastructure development, technology adoption, and workforce training, by evaluating their influence on port performance and strategic objectives. By utilizing Lean Manufacturing and Digital Network Management Analytics to enhance operational efficiency, mitigate risks, and optimize resource allocation, Supply Chain Management ports can attain a competitive edge in the context of Industry 5. Ports that effectively employ these methods can enhance their appeal to shipping lines, logistics providers, and cargo owners, thus bolstering their position in the global supply chain network.

Both LMAW and DNMA offer flexible frameworks that can integrate emerging technologies and trends related to Industry 5, including Internet of Things (IoT), artificial intelligence (AI), and blockchain. Through the integration of these technologies, supply chain management (SCM) ports can seize opportunities for innovation and transformation in their operations.

For the conclusion and pointing out the research contribution and data analysis, the following points are highlighted:

1. Using Fuzzy LMAW, important factors affecting the selection of sea ports were ranked. The results indicated that supply chain best practices, risk identification and contingency management, and enhanced security had the same highest weight among them.
2. Subsequently, based on DNMA, these ports were ranked. The results revealed that among Valparaíso, San Antonio, Coquimbo, and Lirquen, the port of Valparaíso had the highest priority, suggesting that blockchain technology in supply chain management should be implemented in this port.
3. The outcomes of this paper demonstrated that among the applied hybrid MCDA methods in an uncertain environment, the new literature review on implementing BT in SCM during the Industry 5.0 era expanded and highlighted the most important ports and factors.

It is essential to note that the study's findings may not be generalizable to other contexts or industries due to its narrow focus. Additionally, the approach utilized to address obstacles to adopting blockchain technology may not be transferable to other situations. Factors influencing BT implementation in SCM may vary significantly in different geographical regions or industries, thus limiting the broader applicability of the results. Temporal limitations exist due to the study's reliance on data from a specific time point, potentially neglecting the dynamic nature of BT implementation in SCM. The factors affecting the adoption of BT and the readiness of seaports may change over time, highlighting the need for ongoing monitoring and updating of strategies. The assumption of homogeneity in this study may overlook the unique characteristics and challenges specific to individual Chilean seaports. Port-specific nuances and contextual factors could influence the readiness and prioritization of BT implementation, which may not be adequately captured in the analysis.

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References

1. Durán, C.A.; Córdova, F.M.; Palominos, F. A conceptual model for a cyber-social-technological-cognitive smart medium-size port. *Procedia Comput. Sci.* **2019**, *162*, 94–101. [CrossRef]
2. Molavi, A.; Lim, G.J.; Race, B. A framework for building a smart port and smart port index. *Int. J. Sustain. Transp.* **2020**, *14*, 686–700. [CrossRef]
3. Hossain, T.; Adams, M.; Walker, T.R. Role of sustainability in global seaports. *Ocean Coast. Manag.* **2020**, *202*, 105435. [CrossRef]
4. Chen, J.; Huang, T.; Xie, X.; Lee, P.T.W.; Hua, C. Constructing governance framework of a green and smart port. *J. Mar. Sci. Eng.* **2019**, *7*, 83. [CrossRef]
5. Rüßmann, M.; Lorenz, M.; Gerbert, P.d.S.; Waldner, M.; Justus, J.; Engel, P.; Harnisch, M.J. Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries. *Boston Consult. Group* **2016**, *9*, 54–89.
6. Triska, Y.; Frazzon, E.M.; Silva, V.M.D.; Heilig, L. Smart port terminals: Conceptual framework, maturity modeling and research agenda. *Marit. Policy Manag.* **2024**, *51*, 259–282. [CrossRef]
7. De la Pena Zarzuelo, I.; Freire Soeane, M.J.; Lopez Bermudez, B.X. Industry 4.0 in the port and maritime industry: A literature review. *J. Ind. Inf. Integr.* **2020**, *20*, 100173. [CrossRef]
8. Fahim, P.B.M.; An, R.; Rezaei, J.; Pang, Y.; Montreuil, B.; Tavasszy, L. An information architecture to enable track-and-trace capability in Physical Internet ports. *Comput. Ind.* **2021**, *129*, 103443. [CrossRef]
9. Li, K.X.; Li, M.; Zhu, Y.; Yuen, K.F.; Tong, H.; Zhou, H. Smart port: A bibliometric review and future research directions. *Transp. Res. E Logist.* **2023**, *174*, 103098. [CrossRef]
10. Jafari, N.; Azarian, M.; Yu, H. Moving from Industry 4.0 to Industry 5.0: What are the implications for smart logistics? *Logistics* **2022**, *6*, 26. [CrossRef]
11. Durán, C.; Derpich, I.; Carrasco, R. Optimization of Port Layout to Determine Greenhouse Gas Emission Gaps. *Sustainability* **2022**, *14*, 13517. [CrossRef]
12. Ghobakhloo, M.; Iranmanesh, M.; Mubarak, M.F.; Mubarik, M.; Rejeb, A.; Nilashi, M. Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values. *Sustain. Prod. Consum.* **2022**, *33*, 716–737. [CrossRef]
13. Ghobakhloo, M.; Iranmanesh, M.; Morales, M.E.; Nilashi, M.; Amran, A. Actions and approaches for enabling Industry 5.0-driven sustainable industrial transformation: A strategy roadmap. *Corp. Soc. Responsib. Environ.* **2023**, *30*, 1473–1494. [CrossRef]
14. Maddikunta, P.K.R.; Pham, Q.V.; Prabadevi, B.; Deepa, N.; Dev, K.; Gadekallu, T.R.; Ruby, R.; Liyanage, M. Industry 5.0: A survey on enabling technologies and potential applications. *J. Ind. Inf. Integr.* **2022**, *26*, 100257. [CrossRef]
15. Wong, K.H.; Shou, E.C.; Zhang, H.; Ng, A.K. Strategy formulation of new generation ports: A case study of Hong Kong International Terminals Ltd. (HIT). *Res. Transp. Bus. Manag.* **2017**, *22*, 239–254. [CrossRef]
16. Durán, C.A.; Fernández-Campusano, C.; Carrasco, R.; Vargas, M.; Navarrete, A. Boosting the decision-making in smart ports by using blockchain. *IEEE Access* **2021**, *9*, 128055–128068. [CrossRef]
17. Tsiulin, S.; Reinau, K.H.; Hilmola, O.-P.; Goryaev, N.; Karam, A.; Mostafa, A. Blockchain-based applications in shipping and port management: A literature review towards defining key conceptual frameworks. *Rev. Int. Bus.* **2020**, *2*, 201–224. [CrossRef]
18. Zhou, Y.; Soh, Y.S.; Loh, H.S.; Yuen, K.F. The key challenges and critical success factors of blockchain implementation: Policy implications for Singapore's maritime industry. *Mar. Policy* **2020**, *122*, 104265. [CrossRef]
19. Jović, M.; Tijan, E.; Žgaljić, D.; Aksentijević, S. Improving maritime transport sustainability using blockchain-based information exchange. *Sustainability* **2020**, *12*, 8866. [CrossRef]
20. Leng, J.; Sha, W.; Wang, B.; Zheng, P.; Zhuang, C.; Liu, Q.; Wuest, T.; Mourtzis, D.; Wang, L. Industry 5.0: Prospect and retrospect. *J. Manuf. Syst.* **2022**, *65*, 279–295. [CrossRef]

21. Bauk, S. Blockchain conceptual framework in shipping and port management. In Proceedings of the International Conference on Maritime Transport—9th International Conference on Maritime Transport (Maritime Transport IX), Barcelona, España, 27–29 June 2022. [CrossRef]
22. Feng, L.; Shao, E. Strategies and Challenges of Shipping Supply Chain Operating System under Blockchain Technology. *Highlights Bus. Econ. Manag.* **2023**, *11*, 161–168. [CrossRef]
23. Yang, Y.; Zhong, M.; Yao, H.; Yu, F.; Fu, X.; Postolache, O. Internet of things for smart ports: Technologies and challenges. *IEEE Instrum. Meas. Mag.* **2018**, *21*, 34–43. [CrossRef]
24. Papadakis, M.N.; Kopanaki, E. Innovative maritime operations management using blockchain technology & standardization. *J. ICT Stand.* **2022**, *10*, 469–507. [CrossRef]
25. Ahmad, R.W.; Hasan, H.; Jayaraman, R.; Salah, K.; Omar, M. Blockchain applications and architectures for port operations and logistics management. *Res. Transp. Bus. Manag.* **2021**, *41*, 100620. [CrossRef]
26. Balci, G.; Surucu-Balci, E. Blockchain adoption in the maritime supply chain: Examining barriers and salient stakeholders in containerized international trade. *Transp. Res. E Logist.* **2021**, *156*, 102539. [CrossRef]
27. Karaś, A. Smart port as a key to the future development of modern ports. *TransNav Int. J. Mar. Navig. Saf. Sea Transp.* **2020**, *14*, 27–31.
28. Heikkilä, M.; Saarni, J.; Saurama, A. Innovation in Smart Ports: Future Directions of Digitalization in Container Ports. *J. Mar. Sci. Eng.* **2022**, *10*, 1925. [CrossRef]
29. Zhang, Z.; Song, C.; Zhang, J.; Chen, Z.; Liu, M.; Aziz, F.; Kurniawan, T.A.; Yap, P.S. Digitalization and innovation in green ports: A review of current issues, contributions and the way forward in promoting sustainable ports and maritime logistics. *Sci. Total Environ.* **2023**, *912*, 169075. [CrossRef]
30. Wamba, S.F.; Queiroz, M.M. Blockchain in the operations and supply chain management: Benefits, challenges and future research opportunities. *Int. J. Inf. Manag.* **2020**, *52*, 102064. [CrossRef]
31. Bauk, S. Maritime Blockchain Conceptual Framework and Blockshipping Application. In Proceedings of the 11th Mediterranean Conference on Embedded Computing (MECO), Budva, Montenegro, 7–10 June 2022. [CrossRef]
32. Bauk, S.; Ntshangase, L.H. Maritime Blockchain Constraints' Analysis by ISM and MICMAC Techniques. In Proceedings of the 12th Mediterranean Conference on Embedded Computing (MECO), Budva, Montenegro, 6–10 June 2023. [CrossRef]
33. Kasaei, A.; Albadvi, A. Cargo chain: Cargo Management in Port Logistics with Blockchain Technology. *Res. Sq.* 2023, *preprint*. [CrossRef]
34. Serra, P.; Fancello, G.; Tonelli, R.; Marchesi, L. Application Prospects of Blockchain Technology to Support the Development of Interport Communities. *J. Comput.* **2022**, *11*, 60. [CrossRef]
35. Breque, M.; Nul, L.D.; Petridis, A. *Industry 5.0: Towards a Sustainable, Humancentric and Resilient European Industry*; Publications Office of the European Union: Luxembourg, 2021. [CrossRef]
36. Hasan, M.; Haque, Z.; Nazir, S. An evaluation of maritime simulators from technical, instructional, and organizational perspectives: A hybrid multi-criteria decision-making approach. *WMU J. Marit. Aff.* **2023**, 1642–1654. [CrossRef]
37. Park, C.; Kontovas, C.; Yang, Z.; Chang, C.-H. A BN driven FMEA approach to assess maritime cybersecurity risks. *Ocean Coast. Manag.* **2023**, *235*, 106480. [CrossRef]
38. Yazir, D. A survey on MCDM approaches for maritime problems. *Mersin Univ. J. Marit. Logist. Res.* **2023**, *5*, 1–37. [CrossRef]
39. Bahri, M.S.S.; Shariff, S.S.R.; Yahya, N. Comparative analysis on decision criteria for port personnel using hybrid Analytical Hierarchy Process (H-AHP). *Int. J. Anal. Hierarchy Process* **2022**, *14*, 3. [CrossRef]
40. Pazzini, M.; Corticelli, R.; Lantieri, C.; Mazzoli, C. Multi-Criteria Analysis and Decision-Making Approach for the Urban Regeneration: The Application to the Rimini Canal Port (Italy). *Sustainability* **2023**, *15*, 772. [CrossRef]
41. Jin, G. Selection of virtual team members for smart port development projects through the application of the direct and indirect uncertain TOPSIS method. *Expert. Syst. Appl.* **2023**, *217*, 119555. [CrossRef]
42. Argyriou, I.; Sifakis, N.; Tsoutsos, T. Ranking measures to improve the sustainability of Mediterranean ports based on multicriteria decision analysis: A case study of Souda port, Chania, Crete. *Environ. Dev. Sustain.* **2022**, *24*, 6449–6466. [CrossRef]
43. Panaro, S.; Poli, G.; Botte, M.; Sacco, S.; Cerreta, M. Assessing the sustainability of the city-port transformations: Multi-Criteria Decision Analysis (MCDA) for alternatives portfolio selection. *J. Valori E Valutazioni* **2023**, *32*, 91–105. [CrossRef]
44. Pamucar, D.; Žižović, M.; Biswas, S.; Božanić, D. A new logarithm methodology of additive weights (LMAW) for multi-criteria decision-making: Application in logistics. *FU Mech. Eng.* **2021**, *19*, 361–380. [CrossRef]
45. Wilkin, T.; Beliakov, G. Weakly monotonic averaging functions. *Int. J. Intell. Syst.* **2015**, *30*, 144–169. [CrossRef]
46. Lucca, G.; Sanz, J.A.; Dimuro, G.P.; Bedregal, B.; Mesiar, R.; Kolesarova, A.; Bustince, H. Preaggregation functions: Construction and an application. *IEEE Trans. Fuzzy Syst.* **2015**, *24*, 260–272. [CrossRef]
47. Pereira, G.; Bedregal, B.; Bustince, H.; Fernandez, R.; Lucca, G.; Mesiar, R. New results on pre-aggregation functions. In *Uncertainty Modelling in Knowledge Engineering and Decision Making—Proceedings of the 12th International FLINS Conference*; World Scientific: Singapore, 2016; pp. 213–219.
48. Karczmarek, P.; Gregosiewicz, A.; Lagodowski, Z.; Dolecki, M.; Galka, L.; Powroznik, P.; Pedrycz, W. Smooth and Enhanced Smooth Quadrature-Inspired Generalized Choquet Integral. *SSRN eLibr.* **2023**, 1–3. [CrossRef]
49. Hait, S.R.; Dutta, B.; Guha, D.; Chakraborty, D. Improved Bonferroni mean operator to apprehend graph based data interconnections with application to the Hacker Attack system. *Infor. Sci.* **2022**, *616*, 276–302. [CrossRef]

50. Yager, R. On generalized Bonferroni mean operators for multi-criteria aggregation. *Internat. J. Approx. Reason.* **2009**, *50*, 1279–1286. [CrossRef]
51. Liao, H.; Wu, X. DNMA: A double normalization-based multiple aggregation method for multi-expert multi-criteria decision making. *Omega* **2020**, *94*, 102058. [CrossRef]
52. Crisp, J.; Pelletier, D.; Duffield, C.; Adams, A.; Nagy, S.U.E. The delphi method? *J. Nurs.* **1997**, *46*, 116–118. [CrossRef]