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Performance Evaluation of Major World Container Ports in the Post-pandemic Era: The 6th Generation Ports Model with Smart Ports

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Abstract:

The port sector **faces** both challenges and opportunities in digital transformation and decarbonisation in the post-pandemic era. To address these issues, the Sixth Generation Port (6GP) model with smart ports comprising six aspects and 14 criteria was proposed, iteratively refined, and validated. **In order to extend the test scope and assess the applicability of the 6GP model, this study aims to evaluate the performance of major world container ports, namely the Port of Singapore, Shanghai, Busan, Hong Kong, and Rotterdam, by applying the 6GP model with smart ports. An innovative hybrid methodology integrating CFPR, MOORA, and VIKOR was employed to explore the business needs and development priorities of port stakeholders and to assess each port's performance with reference to the 6GP model.** The test results indicate that the Port of Singapore, Rotterdam, and Shanghai performanc, with Asian container ports achieved better performance in "service" and "smart port governance system and policy". Specifically, Shanghai has emphasized automation optimisation to facilitate the seamless cargo and vessel flows, while Rotterdam achieved **significant** performance in digitalisation and decarbonisation by fostering a smart port–city symbiosis. **The contribution of this study lies in theoretical, methodological, and empirical aspects. i) Theoretically, it validates the applicability of the 6GP model, enriching the existing literature on Port Devolution Theory by integrating digitalisation and decarbonisation into the 6GP model; ii) Methodologically, it applies a novel hybrid CFPR–MOORA–VIKOR framework to enhance multi-criteria decision-making in port studies; iii) Empirically, it offers a comparative evaluation of container ports in both Asia and Europe, providing actionable insights for policymakers and port managers, and advocates collaborative action among different stakeholders.**

Keywords: Sixth Generation Ports (6GP); Port digitalisation; Maritime industry decarbonisation; COVID-19; Container port.

1. Introduction

The COVID-19 pandemic caused unprecedented disruption throughout the global supply chains, exerting significant impacts on the port sectors which serve as pivotal nodes of the global trade network. Despite the end of the pandemic, ports remain in a post-pandemic recovery phase, facing challenges but also opportunities arising from accelerated digital transformation and decarbonisation. At the same time, digitalisation has emerged as a key driver of this transformation, integrating technologies such as artificial intelligence, blockchain, and the Internet of Things into port operations to improve efficiency and resilience (Wang and Pettit, 2022). From real-time cargo tracking and optimization of terminal operations to predictive maintenance and automated logistics, digitalisation has reshaped port management paradigms. It also fosters collaboration and information sharing among stakeholders, enhancing overall supply chain efficiency and customer satisfaction. Simultaneously, the global imperative for sustainability has placed ports under pressure to advance decarbonisation, in line with initiatives such as the International Maritime Organization's (IMO) Sulphur Emissions Regulation 2020, its GHG Strategy, and the Paris Agreement. These frameworks underscore the urgency of reducing emissions and promoting greener operations. (Song et al., 2023)

In light of the ongoing transformation in the port industry, this study addresses several critical research gaps. Theoretically, despite advancements in port operation and management, existing port generation models (e.g., the first-generation port (1GP) to fourth-generation port (4GP) models proposed by UNCTAD, 1992, 1999, the fifth-generation port (5GP) model by Lee et al., 2015, 2016; and the sixth-generation port (6GP) model by Song et al., and Lee et al., 2024) have not adequately addressed the profound impacts of COVID-19, digitalisation, and decarbonisation in the port industry (CDD). Moreover, while the 5GP model has been empirically tested across major container ports worldwide, the updated 6GP model has yet to undergo comprehensive global validation. No study has systematically assessed whether ports meet the 6GP standards, nor has the model's effectiveness been tested across different regions. Methodologically, existing performance evaluations predominantly rely on traditional, single-method approaches, which often require large data sets and have inherent limitations. These methods, while useful, face challenges in fully capturing the complexities of port performance, particularly in the context of evolving global challenges.

Against this backdrop, this study aims to evaluate the performance of major container ports globally in the context of the 6GP model with smart ports in the post-pandemic era. By examining the intersection of port performance with focal issues in the port industry, such as digitalization and decarbonization, the key drivers, challenges, and impacts of the ongoing transformation within the global port industry are identified. Further, development priorities from different stakeholders' perspectives are explored, providing insights for port stakeholders including shipping companies, port authorities, freight forwarders, and port experts. Building on this rationale, the explicit objective of this study is to assess the performance of major world container ports ranked in the global top ten by throughput, while simultaneously examining the applicability of the 6GP model in the context of smart ports through the use of an innovative hybrid methodology (CFPR–MOORA–VIKOR). Beyond its objective, the contributions of this study are threefold:

- i) From a theoretical perspective, it advances port governance research by extending Port Devolution Theory through the integration of digitalisation and decarbonisation dimensions into the sixth-generation port (6GP) model;
- ii) From a methodological perspective, it introduces and applies a novel hybrid framework (CFPR–MOORA–VIKOR), enhancing the efficiency, reliability, and applicability of multi-criteria decision-making methods in maritime studies;
- iii) From an empirical and managerial perspective, it offers a comparative evaluation of leading global container ports, providing actionable insights for port authorities, shipping companies, and policymakers to strengthen resilience, competitiveness, and sustainability in the post-pandemic era.

The rest of this paper is organized as follows. Section 2 reviews the literature on smart port developments in Asia and Europe, and introduces the theoretical background and conceptual development of the 6th generation port (6GP) model. Section 3 outlines the research methodology and data collection techniques used. Section 4 presents and analyzes the test results. Section 5 discusses the implications of these results for global port operations. Section 6 concludes with a synthesis of findings and recommendations for future research.

2. Literature Review

2.1 Comparison of smart port development between Asia and Europe

Smart ports represent a pivotal transformation in the maritime industry, where digitalization, automation, and advanced management strategies converge to enhance operational efficiency and sustainability. These ports utilize technologies such as IoT, AI, blockchain, and big data analytics to streamline operations, improve safety, and minimize environmental impact. As defined by SINAY Maritime Data Solution (2023), the development of a smart port involves a strategic framework that encompasses five crucial steps, aiming to elevate a port's management efficiency and adaptability in response to dynamic global demands. These steps include selecting key management areas, identifying the port's maturity level, developing strategies based on this maturity, implementing these strategies, and ensuring the achievement of strategic goals. The management areas crucial for smart port operations are innovation management, technological development, safety and security, environmental management, logistics and hinterland development, operations management, cluster management, administrative management, trade management, and manpower management. This framework provides a structured approach to transforming traditional ports into smart ports, focusing on comprehensive development to meet both operational demands and sustainable practices.

Smart port developments in Asia and Europe showcase a dynamic integration of technological advancements and strategic orientations that reflect their regional priorities and global economic roles. Asian ports are rapidly deploying technologies to increase throughput efficiency and cope with larger cargo volumes, driven by their strategic positions in global manufacturing and trade networks. Leading ports Singapore, Shanghai, Ningbo-Zhoushan, and Qingdao emphasize technological efficiency and automation to enhance cargo handling capacities and operational efficiency (Chen, 2021). The Port of Singapore, notably, utilizes automated yard cranes and drone surveillance to enhance operational efficiency and security. Shanghai Port, employs IoT and big data analytics to optimize shipping routes and terminal

operations. Ningbo-Zhoushan uses 5G and satellite technology to facilitate real-time operations control, whereas Qingdao Port is noted for its pioneering overhead container mono-rail system, which connects different terminal operations to streamline logistics.

In contrast, European ports such as Rotterdam, Hamburg, and Antwerp prioritize digitalization strategies that emphasize sustainability and community integration. Rotterdam Port Authority has implemented advanced systems for energy management and a digital twin of the port to simulate logistics processes and optimize the energy consumption of operations (Port of Rotterdam, 2024). Hamburg Port focuses on renewable energy and advanced sensor technologies to enhance ecological efficiency and manage traffic flows effectively (Hamburg Port Authority, 2024). The Port of Antwerp integrates digital twins and real-time decision-making platforms to bolster operational safety and efficiency (Port of Antwerp-Bruges, 2024). These ports exemplify a holistic approach to smart port development that includes not only technological enhancements but also a strong emphasis on environmental sustainability and community integration.

The differing approaches reflect broader policy orientations. Asian port development is heavily influenced by centralized governmental directives that prioritize technological advancements in port operations as seen in the widespread adoption of automated systems and advanced data analytics. European port development, on the other hand, often follows a bottom-up approach that incorporates extensive stakeholder involvement, focusing on sustainable practices and community benefits, reflecting a more integrated model of port-city relations.

In summary, Asian ports are proactively deploying advanced technologies to enhance operational efficiency and accommodate larger cargo volumes. Concurrently, European ports are strategically integrating digital solutions to streamline operations and mitigate environmental impacts, with the goal of achieving carbon neutrality and fostering improved integration between ports and city infrastructure. This underscores that the development of smart ports transcends mere technological adoption, it necessitates a holistic integration of these technologies within a broader strategic framework that addresses economic, environmental, and social dimensions.

Furthermore, the different development strategies between Asian and European ports prompt a question: Is one approach superior to the other, or do these strategies reflect differing regional priorities and contexts that defy direct comparison? This discussion is not only pertinent but also suggests that comparative research could serve as a valuable platform for cross-regional dialogue and learning, encouraging ports from both Asia and Europe to exchange insights and better practices, thereby enriching the global discourse on sustainable port development.

2.2 Theoretical background with conceptual development of the 6th generation port (6GP) model

In reflecting on the multifaceted challenges and opportunities facing the port industry in recent years, especially the fusion technology, the concept of the 6GP model with smart ports has been proposed (Lee et al., 2020; Song et al., 2022). This conceptual model builds upon earlier iterations, including the initial first-generation port (1GP) model to the fourth-generation port (4GP) model proposed by UNCTAD (1999). Beresford et al. (2004) and Pettit and Beresford (2009) contributed to the port devolution literature by criticising and adding missing port functions to 4GP. Subsequently, discussions on port generation evolved with the introduction

of the fifth generation port (5GP) model, characterized as a "customer-centric community port". This 5GP was further refined by Flynn et al. (2011) and Lee and Lam (2016), and empirically tested by Lee et al. (2018). Lee et al. (2018) tested the 5GP, focusing on the performance evaluation of major container ports in Asia (e.g., Busan, Hong Kong, Singapore, and Shanghai ports), revealing that the Singapore and Hong Kong ports are closely aligned with the criteria of 5GP, whereas Busan and Shanghai ports are lagging in meeting most of the criteria of the 5GP. With the introduction of the 6GP, an initial empirical study of 6GP was conducted by Song et al. (2024), which confirmed its feasibility by evaluating the performance of the top six container ports in mainland China under the 6GP criteria, offering insights into contemporary challenges in the port industry. Table 1 introduces the "Aspects", "Features", and specific "Criteria" of the 6GP.

Table 1 – Aspects, Features, and Criteria of the 6th Generation Port (6GP) Model

Aspects	Features	Criteria
(A) Service	Customer-centric Service	(A1) Reliability
		(A2) Efficiency
(B) Smart technology	Smart technology platform with digitalization	(B1) Establishment of smart technology platform with digitalization
		(B2) Information network security and stability
(C) Sustainability	Symbiosis of port and city	(C1) Coordination/collaboration of port-city interface development
	Resilient system	(C2) Intelligent monitoring and fault response system
	Decarbonization	(C3) Decarbonization management and policy
(D) Cluster	Clustering	(D1) Port industry clustering
		(D2) Maritime and technology industry clustering
(E) Hub	Infrastructure	(E1) Software and hardware infrastructure
	Foreland link	(E2) Shipping service connectivity
	Hinterland link	(E3) Hinterland connectivity
(F) Smart port governance system and policy	Transparency of smart port governance with consistency of smart policy	(F1) Transparency of smart port governance
		(F2) Consistency of smart port policy

Notes: The authors modified the 5GP concept model in Lee et al. (2018, Table 1 on p. 1101), which was reprinted in UNESCAP (2021), and the 6GP concept model in Song et al. (2022, pp. 10–11).

Source: Lee et al. (2023, p. 5).

Nevertheless, considering the emerging issues facing the port industry such as the CDD, the 6GP model has undergone iterative refinement, revising aspects, features and criteria building upon these foundational concepts and empirical findings in Lee et al. (2024). The newly updated 6GP model consists of six aspects, "Service", "Smart technology", "Sustainability", "Cluster", "Hub", and "Smart port governance system and policy". Under these aspects, there are 10 features and 14 criteria (see Table 1). Through iterative refinement, the updated 6GP model aims to provide a comprehensive framework of contemporary ports in the post-pandemic era and beyond. However, this updated 6GP model has not yet been empirically validated and previous empirical cases for generation port models were limited to China or Asia, with no demonstration cases from major container ports worldwide.

Considering the research background and gaps, this paper tests the revised 6GP model, taking major container ports beyond mainland China, such as Singapore, Shanghai, Busan, Hong

Kong, and Rotterdam ports. Recognizing the criteria differences in port management and development policies between Asia under the Asian Port Doctrine (Lee and Flynn, 2011) and Europe under the European Continental Doctrine (Alan and Walters, 1979), this chapter assumes that there may be differences and peculiarities in evaluating the performance of the updated 6GP model with smart ports between Asia and Europe. This study evaluates the performance of six aspects, ten features, and 14 criteria of the 6GP model, encompassing five major container ports worldwide (refer to Table 1).

3. Research Methodology and data collection

This section describes the hybrid methodology combined with the data collection process, using three methods, the Consistent Fuzzy Preference Relation (CFPR), the Multi-Objective Optimization based on Ratio Analysis (MOORA), and the Vlsekriterijumska Optimizacija i KOmpromisno Resenje (VIKOR), to evaluate the performance of major container ports worldwide. Considering that detailed discussions on CFPR¹ and VIKOR² available in previous studies, this section briefly introduced these methods while focusing primarily on the MOORA technique. Building on these three foundational methods, this section proposes an innovative MCDM approach that synthesizes these techniques to provide a more accurate and comprehensive assessment of port performance (see Figure 1).

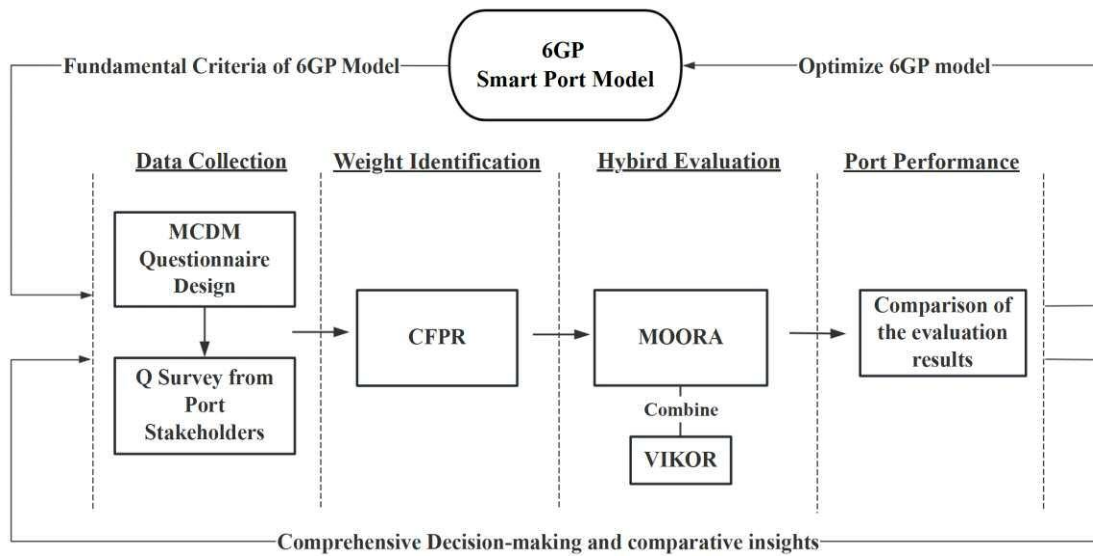


Figure 1. Framework of methodologies combination

3.1 Framework of Methodologies Combination

The CFPR method was used to identify the weights, which is superior to other weighting methods in that it effectively reduces information demand while ensuring the validity of the survey, enhancing the investigative efficacy (Herrera-Viedma et al., 2004). The CFPR method ensures consistency in decision-making by examining the transferability property in fuzzy preference relations. Specifically, it characterizes the consistency through the additive

¹ See Herrera et al. (2004), Lee et al. (2018), Lin et al. (2022), and Song et al. (2024) for further details on this method.

² See Opricovic and Tzeng (2004), Lee et al. (2018), and Kuo (2011) for further details on this method.

transitivity property of fuzzy preference relations, constructing consistent fuzzy preference relations from a set of preference data. This approach enhances the reliability of the preference relations provided by decision-makers, avoiding inconsistent solutions in the decision-making processes.

Second, MOORA and VIKOR methods serve as a rank identification mechanism for the target ports, facilitating an efficient performance assessment. The rationale behind using both methods simultaneously lies in their complementary nature. The MOORA method offers a straightforward ranking mechanism that identifies the relative positions of ports based on the 6GP criteria, characterized by low calculation complexity, robust results, and expedited processing time. Introduced by Brauers and Zavadska (2006), the MOORA method integrates ratio analysis, reference point, and full multiplicative form methods. Chakraborty (2011) reported the advantages of the MOORA method over traditional multi-criteria decision-making methods such as AHP, TOPSIS, ELECTRE, and PROMETHEE, particularly regarding computation efficiency and stability. The MOORA method has been applied in various studies to efficiently solve complex decision-making problems, including the material selection and examining factors affecting the operational and financial performance of third-party logistics service providers (Karande and Chakraborty, 2012; Pal Singh et al., 2022).

VIKOR, complements the MOORA method by serving as a verification method to ensure the robustness and consistency of the evaluation results and provides a ranking system based on a compromise solution among conflicting criteria. This method introduces an aggregating function representing the distance from the ideal solution, balancing overall satisfaction with individual preferences. As proposed by Opricovic and Tzeng (2004), the VIKOR method determines a compromise solution that results in maximum "group utility" for the "majority" while minimum "individual regret" for the "opponent." Lee et al. (2018) and Song et al. (2024) introduced the detailed working principles of the VIKOR method. This combination leverages the strengths of both methods, enhancing the reliability and validity of the evaluation framework. By integrating the MOORA and VIKOR methods, this hybrid method offers a comprehensive and credible evaluation of port performance, meeting the diverse needs of the stakeholders involved.

This holistic approach comprising the CFPR–MOORA–VIKOR methods provides a comprehensive assessment framework for the 6GP model, incorporating quantitative and qualitative dimensions and offering insights into the dynamics of smart port development and governance. Hence, this hybrid method can distinguish which ports conform to the 6GP model with smart ports or identify the aspects in which ports deviate from meeting the criteria to become the 6GP model with smart ports.

3.2 Weights Identification Method: Consistent Fuzzy Preference Relation (CFPR)

To identify the relative importance of the evaluation criteria under the 6GP model, this study adopts the Consistent Fuzzy Preference Relation (CFPR) method. Instead of the multiplicative

preferences commonly used in traditional AHP, the CFPR method offers advantages in reducing the number of required pairwise comparisons (only $n-1$ for n criteria), enhancing consistency, and supporting reliable judgment integration from multiple experts, particularly in cases involving a large number of criteria (Herrera-Viedma et al., 2004; Lee et al., 2018; Lin et al., 2022; Song et al., 2024).

The CFPR process consists of the following key steps:

Step 1: Transformation from multiplicative to fuzzy preference relations.

The CFPR method begins by transforming the multiplicative preference relation $a_{ij} \in \left[\frac{1}{9}, 9\right]$ into an additive fuzzy preference relation $p_{ij} \in [0, 1]$. The transformation is defined as follows:

$$p_{ij} = g(a_{ij}) = \frac{1}{2} \times (1 + \log_9 a_{ij}) \quad (3-1)$$

Step 2: Construction of Fuzzy Preference Relation Matrix (P)

Within the CFPR framework, a fuzzy preference relation matrix $P = P(p_{ij})$ is constructed for a set of n criteria. Each element $p_{ij} \in [0, 1]$ represents the degree to which criterion x_i is preferred over x_j , as assessed by stakeholders. Formally:

$$P = (p_{ij})_{n \times n}, \text{ where } p_{ij} + p_{ji} = 1, \forall i, j \in \{1, \dots, n\} \quad (3-2)$$

Step 3: Construction of Fuzzy Preference Relation Matrix (P)

To ensure consistency within fuzzy preferences, the CFPR method introduces additive transitivity. The basic consistency condition is:

$$p_{ij} + p_{jk} + p_{ki} = \frac{3}{2} \quad (3-3)$$

When preference relations are consistent, they follow the recursive relationships such as:

$$p_{i(i+1)} + p_{(i+1)(i+2)} + \dots + p_{(j-1)j} = j - i + \frac{1}{2}, \forall i < j \quad (3-4)$$

Step 4: Calculation of the preference matrix elements

Based on the transitivity conditions in Step 3, all elements p_{ij} within the matrix can be calculated systematically, ensuring consistency and reducing redundancy in stakeholder input.

Step 5: Derivation of relative weights

Once the preference matrix is completed, the final weights w_i of each criterion are computed through the average of the p_{ij} values:

$$w_i = \frac{\sum_{j=1}^n p_{ij}}{\sum_{i=1}^n \sum_{j=1}^n p_{ij}} \quad (3-5)$$

This method, as adopted in this paper, provides a consistent and efficient mechanism for quantifying expert and stakeholder preferences, which is essential for the robustness of the port performance evaluation under the 6GP model.

3.3 Ranking methods: the MULTI-MOORA and VIKOR methods

3.3.1 MULTI-MOORA technique with three sub-methods

The MULTI-MOORA method involves a structured decision-making process that combines three sub-methods: The Ratio System, the Reference Point, and the Full Multiplicative Form. This method collectively enhances decision-making by offering diverse perspectives through quantitative analysis. The calculation steps of the MOORA method are detailed in the following steps.

Step 1: Decision Matrix Establishment

The decision matrix X is established, where x_{ij} represents the performance of alternative i under criterion j . If there are m alternatives and n criteria, the alternatives and criteria are denoted as $\{A_1, A_2, \dots, A_m\}$ and $\{C_1, C_2, \dots, C_n\}$, respectively. The matrix, along with the weights or significance coefficients w_j for each criterion, is structured as follows:

$$D = \begin{matrix} & \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} & \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \end{matrix} \quad w = (w_1, w_2, \dots, w_n) \quad \sum w_j = 1 \quad (3-6)$$

Step 2: Normalization of the Decision Matrix:

The performance values were normalized to facilitate comparison across different units and scales. The normalization was performed using the following formula:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (3-7)$$

This step yields a normalized decision matrix where each element r_{ij} represents the standardized performance of alternatives under each criterion.

$$R = \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} & \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \end{matrix} \quad (3-8)$$

Step 3: Application of the MULTI-MOORA Sub-Methods

Sub-method 1: Ratio System (RS)

The Ratio System evaluates alternatives by comparing the sum of weighted performance of beneficial attributes against the sum of weighted negative attributes. The difference indicates the overall merit of each alternative:

$$y_i^* = \sum_{j=1}^g w_j r_{ij} - \sum_{j=g+1}^n w_j r_{ij} \quad (3-9)$$

Where g represents the number of beneficial criteria, and $n - g$ represents the number of non-beneficial criteria. Therefore, the ranking results of the ratio system are as follows.

$$A_{RS}^* = \{A_i \mid \max_i y_i^*\} \quad (3-10)$$

Sub-method 2: Reference Point (RP)

The Reference point approach uses normalized values to set objective benchmarks. For each criterion, select a reference point r_j that represents the ideal performance value. Typically, this reference point corresponds to the maximum value for beneficial criteria and the minimum value for non-beneficial criteria.

$$r_j = \begin{cases} \max_i r_{ij}, & \text{in case of maximization, } n \leq g \\ \min_i r_{ij}, & \text{in case of minimization, } n > g \end{cases} \quad (3-11)$$

For each alternative i and criterion j , calculate the absolute deviation $|r_j - x_{ij}^*|$ from the reference point. This step evaluates how far each alternative is from the ideal performance. The greatest distance to the reference point across all criteria determines the ranking.

$$z_i^* = \max_j \left| (w_j r_j - w_j r_{ij}) \right| \quad (3-12)$$

Alternatives are ranked by minimizing z_i^* where a smaller distance indicates closeness to the ideal.

$$A_{RP}^* = \left\{ A_i \mid \min_i z_i^* \right\} \quad (3-13)$$

Sub-method 3: Full Multiplicative Form (MF)

Developed based on econometric principles (Brauers and Zavadskas, 2011), the full multiplicative form method offers an alternative approach by incorporating the multiplicative relationship of criteria values. This method multiplies the performance indices associated with beneficial attributes and divides by those associated with cost attributes, adjusted for attribute weights:

$$U'_i = \frac{\prod_{j=1}^g (x_{ij})^{w_j}}{\prod_{j=l+g}^n (x_{ij})^{w_j}}, \quad U_i^* = \frac{\prod_{j=1}^g (r_{ij})^{w_j}}{\prod_{j=l+g}^n (r_{ij})^{w_j}} \quad (3-14)$$

Alternatives are ranked by maximizing U_i , where a higher value indicates a better alternative.

$$A_{MF}^* = \left\{ A_i \mid \max_i U_i^* \right\} \quad (3-15)$$

Step 4: Dominance Theory for Final Ranking

In the final stage of the MULTI-MOORA approach, the ranking of alternatives is determined using Dominance Theory, which systematically assesses the relative superiority of each alternative based on its performance across the three sub-methods: Ratio System, Reference Point, and Full Multiplicative Form. Let A (a, b, c) represent the sub-ranking of alternative A under the three sub-methods. The criteria for dominance are as follows:

- 1) Dominance Rule:
 - Absolute Dominance: An alternative is absolutely dominant if it ranks first in all sub-methods, indicated as (1,1,1), showing it surpasses all others.
 - Partial Dominance: An alternative achieves partial dominance if it ranks first in at least two of the sub-methods. For instance, if alternative A ranks (a, a, a) and B ranks (b, b, b) with $a < b$, A fully dominates B. If A's rankings are (a, d, a) against B's (b, c, b), A partially dominates B.

2) Transitivity Rule:

Dominance is transitive; if A dominates B, and B dominates C, then A dominates C. This ensures logical consistency across comparisons.

3) Equality Rule:

- **Absolute Equality:** This occurs when two alternatives have the same rankings across all sub-methods, such as A (a, b, c) and B (a, b, c).
- **Partial Equality:** If two alternatives tie in one sub-method and each dominates the other in a different sub-method, they are considered partially equal.
- **Cyclic Reasoning Equality:** This condition emerges when dominance forms a loop contradicting direct comparisons, leading to a paradox where no clear dominance is established. For example, if A dominates B, B dominates C, but C dominates A, then all three are considered equal.

Applying this MULTI-MOORA approach ensures a thorough and logical assessment of alternatives, enabling well-informed decision-making that accounts for multiple criteria and potential conflicts.

3.3.2 VIKOR method

The VIKOR is an approach that focuses on ranking and selecting from a set of alternatives when multiple, often conflicting, criteria are involved. It introduces the concept of a compromise solution, which is the closest to the ideal, considering both the group utility and the individual regret. In this study, the VIKOR method was applied after obtaining the normalized decision matrix and weights from the preceding steps.

Step 1: Establish the optimal (f^*) and the least favorable (f^-) values of all criterion functions

For benefit criteria, f^* is the maximum observed value and f^- is the minimum; for cost criteria, the opposite applies. Given that the i -th function signifies a benefit:

$$f_i^* = \max_j f_{ij}, f_i^- = \min_j f_{ij} \quad (3-16)$$

Step 2: Compute the utility measure (S_j) and the regret measure (R_j)

The utility measure reflects the overall group utility, while the regret measure represents the maximum individual regret:

$$S_j = \sum_{i=1}^n w_i (f_i^* - f_{ij}) / (f_i^* - f_i^-) \quad (3-17)$$

$$R_j = \max_i [w_i (f_i^* - f_{ij}) / (f_i^* - f_i^-) \mid i=1, 2, \dots, n] \quad (3-18)$$

where w_i is the weight of criterion, and f_{ij} is the performance score of alternative i under criterion j .

Step 3: Evaluate the Q_j values

The Q_j value integrates both S_i and R_i to determine a compromise ranking:

$$Q_j = v(S_j - S^*) / (S^- - S^*) + (1 - v)(R_j - R^*) / (R^- - R^*) \quad (3-19)$$

where:

$$\begin{aligned} S^* &= \min_j S_j, S^- = \max_j S_j \\ R^* &= \min_j R_j, R^- = \max_j R_j \end{aligned} \quad (3-20)$$

ν is the weight of the majority criterion strategy (commonly set to 0.5 in compromise solutions).

Step 4: Determine the final ranking and check acceptable advantage and stability conditions.

Alternatives are ranked by ascending Q values. The compromise solution is acceptable if:

Condition 1. Acceptable threshold:

$$Q(A^{''}) - Q(A') \geq \frac{1}{J-1} \quad (3-21)$$

where $A^{''}$ is the second-ranked alternative, and J is the total number of alternatives.

Condition 2. Decision-making stability:

The best-ranked alternative according to Q must also be ranked first according to S , R , or both. If both conditions are satisfied, A' is the unique compromise solution; otherwise, a set of compromise solutions is proposed.

4. Data collection and test results

For data collection, a validated questionnaire was designed and distributed to four key groups of experts and stakeholders in the port industry, i.e., shipping companies, port authorities, freight forwarders, and port experts. The questionnaire comprised three main sections:

- (i) Section I aimed to evaluate the relative importance of the 6GP evaluation criteria. Respondents were asked to conduct pairwise comparisons of the criteria using a 9-point scale, which was later processed using the CFPR method to derive the final weights. This scale ranged from 1 (equally important) to 9 (extremely more important), enabling the construction of a fuzzy preference matrix.
- (ii) Section II explored the logical consistency and interrelationships among the 6GP criteria. Respondents again used a 9-point comparison scale to evaluate the mutual influence between criteria, supporting the refinement of the decision-making framework and validation of hierarchical relationships.
- (iii) Section III captured stakeholder perceptions of the performance of selected ports with respect to each of the 6GP criteria. Ratings were provided using a 5-point Likert scale (1 = very poor, 5 = excellent), allowing for quantitative performance evaluation across multiple port cases.

For a full description of the questionnaire content and structure, please refer to Appendix: Questionnaire in Song (2025).

Both a pilot survey along with interviews, and the main survey were carried out. The pilot survey was conducted between the end of August to the beginning of September and the beginning of December to mid-December 2023, to assess the appropriateness of the questionnaire design and to identify possible problems in the main survey. Four major stakeholder groups in the shipping industry, namely shipping companies, port authorities, freight forwarders, and port experts, were deliberately selected, with an approximately equal number of participants from each group to ensure balanced representation. Given that professional experience is critical for this type of assessment, respondents were chosen based on their extensive industry backgrounds, with an average of over 20.5 years of experience. Their job titles included Vice President, General Manager, Department Manager, Captain, Senior Pilot, Director, Chief Executive Officer, Chairman of trade organizations, Professors, and Team Leaders of port associations. Nearly all respondents had direct experience using the target ports examined in this study. This diverse and well-balanced sample composition enhances the credibility of the empirical results and ensures that the perspectives captured reflect both strategic and operational viewpoints across the port supply chain. Table 2 provides a detailed profile of the survey respondents, including the number of participants from each stakeholder group, their average years of experience, and their respective job positions. This diverse sample composition enhances the credibility of the empirical results and ensures that the perspectives captured reflect both strategic and operational viewpoints across the port supply chain.

Table 2 – Respondents’ profile of the main questionnaire survey

Respondent group	Number of respondents	Average working years	Job title
Shipping company	8	23.0	Vice President, General Manager, Dept. Captain
Freight forwarder	5	14.4	General Manager, Senior Pilot, Director
Port authority	6	20.7	C.E.O.; General Manager, Dept. Manager
Port Expert	6	22.8	Chairman of trade organization, Professor, Team leader of port association

Source: compiled by author (2024).

4.1 Relative weight of the 6GP criteria based on stakeholder perspectives

This section focuses on the relative importance of the 14 criteria of 6GP evaluated by four groups of stakeholders in the port industry (e.g., shipping companies, port authorities, freight forwarders, and port experts), which reflect the differences in their perceptions of the different criteria during the assessment process. **Figure 2** is organized into the criteria of the 6GP, with corresponding weight values provided by the four groups of stakeholders. The results assist port managers, operators, users, and academics in understanding the different priorities of each other when engaging in port-related business. The average weight takes into account the overall views of the four groups of respondents. Overall, among the 14 criteria, the top three weighted criteria fall within the aspect "E. Hub ", e.g., "(E2) Shipping service connectivity", and the aspect "F. Smart port governance system and policy", e.g., "(F2) Consistency of smart port policy", and "(F1) Transparency of smart port governance". Conversely, the bottom three ranked criteria fall within aspect "C. Sustainability", e.g., "(C1) Coordination/collaboration of port-city interface development", and aspect "A. Service", e.g., "(A2) Efficiency", and "(C3) Decarbonization management and policy".

					Range (Max-Min)	Avg.	Rank
A1	0.070	0.074	0.063	0.069	0.011	0.069	8
A2	0.070	0.059	0.055	0.062	0.015	0.062	13
B1	0.064	0.062	0.059	0.080	0.021	0.066	11
B2	0.071	0.073	0.075	0.073	0.004	0.073	5
C1	0.073	0.049	0.072	0.047	0.026	0.061	14
C2	0.069	0.070	0.076	0.072	0.007	0.072	6
C3	0.057	0.064	0.071	0.066	0.014	0.065	12
D1	0.065	0.071	0.064	0.069	0.008	0.067	10
D2	0.067	0.071	0.068	0.073	0.006	0.070	7
E1	0.078	0.069	0.084	0.082	0.015	0.078	4
E2	0.082	0.080	0.084	0.091	0.010	0.084	1
E3	0.073	0.066	0.072	0.065	0.008	0.069	9
F1	0.079	0.089	0.076	0.078	0.013	0.081	3
F2	0.080	0.102	0.081	0.073	0.029	0.084	2

Shipping Co. Port authority Freight forwarder Port expert

Figure 2. Relative weights of 6GP criteria evaluated by four groups of port stakeholders

In particular, stakeholders from shipping companies, port authorities, and freight forwarders, representing the industry's perspectives of the port, generally share similar views. On the other hand, significant differences in perspectives were noted between these industry stakeholders and port experts (i.e., academics, experts from port associations, and trade organizations). A common view is that all four stakeholder groups consider the criteria "(E2) Shipping service connectivity" to be highly important. Regarding "(B1) Establishment of smart technology platform with digitalization," this was perceived as less critical by the stakeholders from the industry and ranked 12th and 13th out of the 14 criteria. Nevertheless, with an overall ranking of 11, port experts consider it the third most important criterion.

Significant discrepancies in the point of view exist among the four respondent groups regarding the criterion "(C1) Coordination/collaboration of port–city interface development". The port authority and port expert groups perceive this criterion as the least important of the 14 criteria. By contrast, shipping companies and freight forwarder groups ranked it at a relatively more important position, ranking it fifth and seventh, respectively. Hence, shipping companies and freight forwarders recognize the high importance of effective coordination and collaboration between the port and city governments or communities to foster a smart port ecosystem. The reason lies in, for example, collaboration between ports and cities, as well as the development of the 'port-city interface' (waterfront zones where the geography of the port and its city converge), which involves market growth, port competition, value-added economic potential, and commercial interests of their existing and potential customers.

In addition, from the perspective of the regions where the respondents are based, the degree of port–city integration in the five target ports may influence their decision-making. A review of the original survey data showed that respondents who gave higher scores to the criterion "(C1) Coordination/collaboration of port-city interface development" were mainly from Shanghai. In contrast, those who gave lower scores were primarily from Singapore and Busan, while the respondents from Rotterdam had a neutral stance towards this criterion.

A review of the relevant literature showed that the convenience of existing port services in South Korea appears insufficient to guarantee the economic success of the cities where the ports were located, and the local economy may no longer benefit significantly from the nearby ports. Regarding the Port of Shanghai, the integration between the port and the city is crucial because of Shanghai's role as a major global trade hub. Effective coordination and collaboration between the port and the city government are essential for supporting economic growth, enhancing port competitiveness, and maximizing the economic potential of value-added services. In recent years, the Shanghai Municipal Government has made considerable efforts to promote the integration of the port and city through policies and infrastructure projects that aim to enhance the connection between port operations and urban development.

In contrast, the Port of Rotterdam, one of the largest and most advanced ports in Europe, has historically maintained a high level of port-city integration. The port's development has been closely tied to the city's economic strategies, and there is a well-established framework for collaboration between the port authority and the municipal government. This long-standing integration has resulted in a balanced approach where both the port and the city benefit from each other's growth, thereby explaining the neutral stance of respondents from Rotterdam towards this aspect.

The case of Singapore offers another perspective. The Port of Singapore is one of the busiest and most efficient worldwide, playing a pivotal role in the country's economy. Nevertheless, the port–city relationship in Singapore is unique because of the small geographical size and high degree of urbanization of the city-state. The port operations are highly integrated with the national economic strategy, focusing on efficiency and connectivity rather than traditional port-city interface development. The emphasis is on maximizing land use and maintaining the port's competitive edge in the global market, rather than on broader collaboration between the port and city areas. This strategic focus likely contributes to the lower scores from Singaporean respondents for this aspect.

These regional differences highlight how the specific context and historical development of port-city relationships can shape stakeholders' perceptions of the importance of effective coordination and collaboration of the port-city interface. For instance, Shanghai's proactive integration efforts contrast with the more mature and established collaboration frameworks in Rotterdam. At the same time, the situation in South Korea underscores the need for stronger linkages between port success and urban economic development, while Singapore's approach reflects a strategic focus on efficiency and global competitiveness over traditional port-city integration.

From the perspective that different stakeholders in the port sector play different roles in the supply chain ecosystem, each stakeholder group exhibits different roles, responsibilities, and priorities. Shipping companies prioritize ports that provide better software and hardware infrastructure, as well as higher connectivity to the hinterland (E1 and E3), to ensure the efficient movement of goods and smooth port services to meet customer needs. Port authorities, however, emphasize port reliability and information network security (A1 and B2) to ensure the stability and consistency of port operations. On the other hand, freight forwarders place great importance on the reliability of information network monitoring (C2) to obtain timely information on port services and respond quickly to problems that may affect cargo movement, ensuring the smooth transshipment of goods. In addition, port experts consider it vital to build smart technology platforms and digitize port operations (B1). They prioritise technological innovation and digital transformation of ports to improve the efficiency and sustainability of port operations.

In summary, these divergent perspectives derive from the variations in responsibilities, roles, profit drivers, expertise backgrounds, and economic incentives and constraints of different stakeholders, underscoring the dynamics within the maritime supply chain. Understanding these intricacies is essential in devising comprehensive supply chain management strategies tailored to the needs and priorities of each stakeholder group.

4.2 Performance evaluation of the five major container ports in the world

Another major finding of the study lies in assessing the performance of the **five selected ports, as assessed by stakeholders from the four respondent groups based on their practical experience**. The results revealed significant distinctions in the performance among the five ports, particularly between Asia and Europe, across the 14 criteria (see Table 3).

The Port of Singapore **demonstrated** the highest performance across ten criteria, excelling specifically in “Shipping service connectivity,” “Reliability,” and “Efficiency.” The Port of Rotterdam also ranked **highest** in five criteria, particularly in “Establishment of digital smart technology platforms” and “Decarbonization management and policies.” **Both ports received the highest scores in** “Consistency of Smart Port Policies.” In contrast, the Port of Hong Kong **received the lowest performance scores** among the five ports in **11 of the 14 criteria, with the most pronounced performance gap observed in** “Decarbonization management and policy.”

Overall, the Singapore, Rotterdam, and Shanghai ports ranked in the top three in that order, followed by the Busan and Hong Kong ports. **The findings highlight that** the Port of Rotterdam showed better performance than Asian ports in terms of digitalization and decarbonization, while Asian ports (Shanghai and Singapore) achieved better performance in terms of “Services,” “Cluster,” and “Transparency of smart port governance.”

Table 3 – Average performance of 6GP criteria of the five ports

Aspects	Criteria	Weights	Singapore	Shanghai	Busan	Hong Kong	Rotterdam	Max	Min	Range
(A) Service	(A1) Reliability	0.069	4.3	3.5	3.5	3.5	4.0	4.3	3.5	0.8
	(A2) Efficiency	0.062	4.3	4.1	3.6	3.5	4.0	4.3	3.5	0.8
(B) Smart technology	(B1) Establishment of smart technology platform with digitalization	0.066	3.9	3.9	3.3	3.2	4.2	4.2	3.2	0.9
	(B2) Information network security and stability	0.073	4.1	3.7	3.5	3.5	4.2	4.2	3.5	0.7
(C) Sustainability	(C1) Coordination/collaboration of port-city interface development	0.061	4.0	3.6	3.4	3.0	3.8	4.0	3.0	1.0
	(C2) Intelligent monitoring and fault response system	0.072	4.0	3.5	3.6	3.3	3.9	4.0	3.3	0.7
	(C3) Decarbonization management and policy	0.065	3.7	3.2	3.2	2.9	4.2	4.2	2.9	1.3
(D) Cluster	(D1) Port industry clustering	0.067	4.3	3.7	3.4	3.4	3.9	4.3	3.4	1.0
	(D2) Maritime and technology industry clustering	0.070	4.2	3.7	3.3	3.1	4.0	4.2	3.1	1.1
(E) Hub	(E1) Software and hardware infrastructure	0.078	4.2	4.0	3.7	3.5	4.1	4.2	3.5	0.7
	(E2) Shipping service connectivity	0.084	4.6	4.0	3.5	3.7	4.1	4.6	3.5	1.1
	(E3) Hinterland connectivity	0.069	3.5	3.5	3.2	3.4	3.9	3.9	3.2	0.7
(F) Smart port governance system and policy	(F1) Transparency of smart port governance	0.081	4.3	3.7	3.5	3.3	4.1	4.3	3.3	1.0
	(F2) Consistency of smart port policy	0.084	4.3	3.7	3.6	3.3	4.3	4.3	3.3	1.0

4.2.1 Evaluation results using the MULTI-MOORA method

This section presents the results of applying the MULTI-MOORA method to evaluate the performance of the selected major container ports (Singapore, Shanghai, Busan, Hong Kong, and Rotterdam) across the 14 criteria from the perspectives of four stakeholder groups (i.e., shipping companies, port authorities, freight forwarders, and port experts) as well as an overall perspective. The evaluation of the MULTI-MOORA method considered three sub-methods: RS, RP, and MF. Appendix Tables 1(a), 1(b), and 1 (c) list the evaluation results of port

performance using three sub-methods of the MULTI-MOORA method. The ranking of these ports was calculated using three sub-methods that considered their performance under each of the 14 criteria given by the respondents.

The Ratio System method evaluates the performance of each port by calculating the weighted normalized performance scores for both beneficial and non-beneficial criteria. In the Reference Point approach, the maximum deviation from an established reference point (typically the best-performing port for each criterion) is used to evaluate each port. The Full Multiplicative Form method assesses the performance by calculating the product of the weighted normalized scores for beneficial and non-beneficial criteria. These results highlight both the commonalities and differences in port rankings as assessed by these sub-methods across stakeholder groups.

The final ranking is determined using dominance theory, which synthesizes the results of the three sub-methods. The results presented in Table 4 establish the performance of the five target ports from the perspective of the four groups of stakeholders, as well as the overall view.

The Port of Singapore ranks first overall, supported by strong rankings across different stakeholder groups: first by shipping companies and port experts and second by port authorities and freight forwarders, reflecting its strong infrastructure, efficient operations, and advanced technological integration. Rotterdam Port ranks second overall, particularly excelling from the perspectives of port authorities and freight forwarders, while being ranked fourth by shipping companies. Shanghai Port holds a consistent third-place ranking overall, highlighting its significant role in global shipping and potential for further improvement. Busan and Hong Kong generally rank lower, with Busan ranked fifth by shipping companies and freight forwarders, indicating areas where enhancements in operations and services are needed. Hong Kong is ranked fifth by port authorities and port experts.

Table 4 – Final result evaluated by MULTI-MOORA

	Shipping Co.	Port authority	Freight forwarder	Port expert	Overall
Singapore	1	2	2	1	1
Shanghai	2	3	3	3	3
Busan	5	4	5	4	4
Hongkong	3	5	4	5	5
Rotterdam	4	1	1	2	2

The three sub-methods of MOORA i.e., Ratio System, Reference Point Approach, and Full Multiplicative Form, providing different perspectives on evaluating port performance, which can sometimes lead to variations in rankings. For example:

- i) Consistency in Rankings: Singapore consistently ranks highest across all three sub-methods, reflecting its strong and well-rounded performance.
- ii) Variations in Rankings: Differences in rankings for other ports, such as Shanghai and Rotterdam, can arise due to the distinct computational approaches of each sub-method. The Ratio System focuses on the overall balance of beneficial and non-beneficial criteria, the Reference Point Approach emphasizes the proximity to the best-performing

port, and the Full Multiplicative Form considers the multiplicative relationships of criteria.

The observed variations in rankings highlight the importance of using a comprehensive approach like the MULTI-MOORA method, which combines the strengths of multiple sub-methods for a more balanced and thorough evaluation.

4.2.2 Evaluation results using the VIKOR method

This section introduces the VIKOR method, which reflects a compromise solution among the criteria, considering both acceptable advantage (Condition 1) and acceptable stability (Condition 2) criteria to validate and contrast the findings. Table 5 presents the performance evaluated by the four stakeholder groups (shipping companies, port authorities, freight forwarders, and port experts) and an overall perspective.

Across the different stakeholders' perspectives, some common trends and notable differences emerge. Singapore consistently ranks high, often securing the top position, reflecting its robust infrastructure and efficient operations. For example, shipping companies and port experts place Singapore first, highlighting its strong performance in these critical areas. Interestingly, the port experts' rankings closely align with the overall rankings, suggesting that their evaluations strongly reflect the aggregated views. Rotterdam also performs well, particularly from the perspectives of port authorities and freight forwarders, who rank it first. Hence, Rotterdam has strong capabilities in efficiently handling large volumes and diverse cargo. Nevertheless, shipping companies rank Rotterdam fourth, showing a slight divergence in perceptions, which may be due to different priorities or operational experiences.

Shanghai holds a steady third position overall, supported by its consistent rankings across most stakeholder groups. In particular, Shanghai, Rotterdam, and Busan are grouped closely in the rankings provided by the shipping companies, suggesting similar performance levels between them. In particular, the differences between the Q values for Shanghai, Rotterdam, and Busan are less than the acceptable threshold (Condition 1=0.25), suggesting that these ports can be considered equivalent, meaning they are incomparable. Busan and Hong Kong generally rank lower. Busan is frequently placed fourth, while Hong Kong is often last. This pattern suggests that both ports must address specific operational and service-related challenges to enhance their competitive standing. In some evaluations, the close Q values for these ports suggest that while they lag behind the leaders, their performance levels are not vastly different.

These findings highlight the importance of considering multiple perspectives in evaluating the port performance. The consistently high rankings of Singapore and Rotterdam highlight their overall strengths, while the variations in rankings for other ports indicate specific areas requiring attention. Decision-makers can prioritize improvements and develop strategies that address the diverse needs and expectations of different stakeholders by synthesizing these insights. The next section compares the results of the MULTI-MOORA and VIKOR methods to contrast the two methods and obtain the similarities and differences in the insights gained from each method.

4.3 Results comparison between MOORA and VIKOR

The MOORA and VIKOR methods serve as a rank identification mechanism for assessing the port performance. Table 6 and Figure 3 compares the results obtained using the MULTI-MOORA and VIKOR methods. The rankings produced by the MULTI-MOORA and VIKOR methods are consistent, indicating the validity and reliability of the present study. Although the VIKOR method considered some ports to be in the same tier because of the small differences in their scores, the overall ranking remained identical.

Table 6 – Port performance results evaluated by MOORA and VIKOR

Port	Rank by MOORA				Rank by VIKOR		
	Rank by method 1	Rank by method 2	Rank by method 3	Final Rank	Q value	Final Rank	Group
Singapore	1	1	1	1	0.021	1	1
Shanghai	3	3	3	3	0.588	3	2
Busan	4	4	4	4	0.930	4	3
Hong Kong	5	5	5	5	0.996	5	3
Rotterdam	2	2	2	2	0.044	2	1

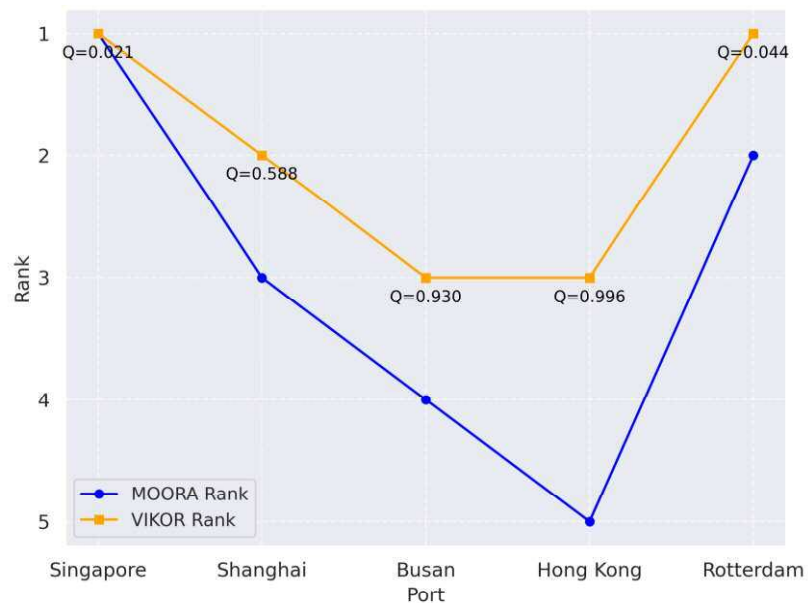


Figure 3. Comparison of Port Rankings: MOORA vs VIKOR

The MULTI-MOORA method ranks the ports in the following order: Singapore, Rotterdam, Shanghai, Busan, and Hong Kong. Nevertheless, although the MULTI-MOORA method provides a clear ranking of the ports, it does not reveal the extent of the differences between them. The VIKOR method, while largely aligning with these rankings, quantifies the performance by providing Q values, allowing an understanding of the rankings and the performance gaps between ports. For example, while Shanghai and Rotterdam were ranked

second and third, respectively, by the MOORA method, their Q values in the VIKOR method suggest that they are indistinguishable because the difference between their scores is minimal.

In summary, the consistency between the MULTI–MOORA and VIKOR results validates the accuracy of this study. Nevertheless, introducing the VIKOR method adds significant value by quantifying the degree of variation between ports. This allows for a more in-depth analysis of the port performance, highlighting which ports are ahead or behind and which are close enough to be considered equivalent. This approach provides a more objective basis for management and decision-making discussions.

5. Discussion and implications

This study empirically tested the 6GP model, considering the major container ports in both Asia and Europe. The test considered the key port performance of 14 criteria of the 6GP from the perspectives of four stakeholder groups, using an innovative hybrid approach CFPR–MOORA–VIKOR.

This study provided a more thorough and reliable evaluation framework for decision-makers in the port and shipping industry by comparing the results from the selected two methods. This comparative analysis highlights the strengths and potential limitations of each method, ensuring a robust decision-making process. **It should be noted that the resulting port rankings are indicative rather than definitive.** This detailed analysis also enhances the understanding and application of advanced hybrid MCDM methods in port performance evaluation, providing insights for stakeholders in the port sector.

In the context of the 6GP model with smart ports, characterized mainly by the CDD, these findings offer significant insights for major container ports with port stakeholders worldwide, especially in the post-pandemic era. The discussions and implications from the test results contribute to the academic and field industry in theoretical, empirical, and managerial dimensions.

5.1 Theoretical insights

This paper contributes to the theoretical advancement of port governance by addressing existing gaps in the literature on port evolution and devolution. Through the empirical validation of the 6GP model in the context of global container ports, this research extends prior work focused on Chinese ports (Song et al., 2024) to a broader global setting. **The application of the 6GP framework to both Asian and European ports marks a key step in evaluating its applicability beyond China.** By incorporating both Asia and Europe, this study makes a novel contribution by assessing the 6GP model in diverse regional contexts, thus offering valuable insights into the global applicability and flexibility of the model in addressing the unique challenges faced by ports in different parts of the world.

The extension of the 6GP model to regions outside China provides a novel perspective on its capacity to accommodate different port governance structures, regulatory environments, and technological capabilities. This empirical expansion is a significant advancement over previous studies that predominantly focused on Chinese ports. Notably, the comparative analysis between Asia and Europe emphasizes the diverse paths toward smart port development under the 6GP framework, shedding light on the different priorities and challenges faced by regions with distinct operational, regulatory, and technological conditions.

From a comparative research perspective, the empirical expansion of this study to include container ports in both Asia and Europe offers critical insights into the differentiated pathways of smart port development across regional contexts. **This cross-regional analysis underscores the importance of adapting the 6GP model to fit the local characteristics and evolving needs of each region.** For example, ports such as Singapore and Shanghai exhibit strong performance in service-related dimensions and transparent governance mechanisms, while European ports, especially Rotterdam, excel in areas related to digitalization and decarbonization. These findings highlight the necessity for nuanced strategic planning that aligns with regional characteristics and leverages specific advantages to address emerging global port challenges.

5.2 Methodological insights

From a methodological perspective, this thesis advances the application of hybrid multi-criteria decision-making methods in maritime studies by employing a novel CFPR-MOORA-VIKOR integration. **This hybrid methodology combines the strengths of multiple approaches, offering a comprehensive and credible evaluation of port performance.** It addresses several limitations found in traditional optimization methods, namely, high data input requirements and limited computational efficiency. **The integration of these methods provides dual validation of results, complements the limitations of single-method approaches, reduces data requirements, and enhances computational efficiency.**

The VIKOR method complements the MOORA method by serving as a verification tool to ensure the robustness and consistency of the evaluation results. The VIKOR method provides a ranking system based on a compromise solution among conflicting criteria, balancing overall satisfaction with individual preferences. It introduces an aggregating function to measure the distance from the ideal solution, maximizing “group utility” while minimizing “individual regret.” This approach enhances the reliability and validity of the evaluation framework by leveraging the strengths of both MOORA and VIKOR methods, offering a robust and flexible tool that meets the diverse needs of port performance stakeholders.

This holistic approach comprising CFPR–MOORA–VIKOR provides a comprehensive assessment framework for the 6GP model, incorporating both quantitative and qualitative dimensions. The proposed fusion methodologies reduce data requirements and improve computational efficiency while ensuring the reliability of the results. In doing so, it addresses key limitations in existing multi-objective optimization methods.

5.3 Empirical insights with managerial implications

This chapter offers managerial insights into addressing the challenges facing the port industry, particularly the impact of the CDD, referring to the findings of the performance of major container ports by port stakeholder groups. This chapter also provides decision-makers with a holistic view of port development strategies to improve the competitiveness of their ports in the post-pandemic era based on the performance evaluation results (see Table 4). Therefore,

port authorities can prioritize meeting the different business needs of each port user with their limited resources.

The evaluation of port performance revealed notable distinctions among the selected ports, particularly between Asian and European ports. The Port of Singapore demonstrated superior performance across various criteria, emphasizing its prominence in shipping service connectivity, reliability, and efficiency. On the other hand, the Port of Hong Kong exhibited lower performance, particularly in terms of decarbonization management and policy, highlighting areas for improvement.

A notable comparison is made between the results of the 6GP model and previous evaluations under the 5GP criteria. The 5GP model, which included a broader global range of ports, assessed Shanghai Port as the lowest performer among the four major Asian ports (Lee et al., 2018a), underperforming in nine evaluation criteria. In contrast, the findings of the current 6GP-based assessment revealed remarkably improved performance for Shanghai Port. The port now ranks third globally and second in Asia, surpassed only by Singapore. Shanghai Port demonstrated significant progress in several key areas, particularly in service quality, smart governance transparency, and port cluster coordination. This improvement highlights the advancements made by Chinese ports towards becoming smart, sustainable, and resilient logistics hubs.

By expanding the study's focus to include ports beyond China, the 6GP model allows for a direct comparison of the performance of the same ports across the two frameworks (5GP and 6GP). This comparison highlights whether the progress observed in the same port under the 6GP model represents an advancement or regression, providing valuable insights into the global applicability and effectiveness of the 6GP framework. Furthermore, the performance of these ports under the updated 6GP criteria and the previous 5GP model reflects their development status in recent years, serving as a crucial reference for policymakers and port managers, offering guidance for future decision-making and strategic planning in port development and management.

The relative importance of the 14 criteria evaluated by different stakeholder groups (see Table 2) emphasizes diverse perspectives within the port industry. While shipping companies, port authorities, and freight forwarders share common perspectives, the divergent views of port experts (mainly academics) demonstrate the need for a balanced approach and cross-industry dialogue with cooperation. Decision-makers could utilize the evaluation results to prioritize development strategies and allocate resources efficiently. By understanding the dynamic needs of port stakeholders, port operators and users could strategically focus on aspects aligned with their customers' expectations, enhancing the overall system efficiency and improving their competitiveness in the evolving global trade environment.

6. Conclusion

This paper empirically evaluated the 6GP model, taking the major container ports in Asia and Europe (Shanghai, Singapore, Busan, Hong Kong, and Rotterdam), i.e., applying an innovative hybrid approach methodology, the CFPR–MOORA–VIKOR method. This evaluation assessed the applicability of the updated 6GP model through the perceptions of senior and representative experts from four main stakeholder groups in the port industry, rather than through objective

performance indicators or statistical validation. This chapter expands the literature on port devolution and evolution by empirically evaluating the updated 6GP model and validating its applicability to container ports. This comparative analysis highlights the strengths and weaknesses of each region towards the 6GP model. Asian ports (Singapore and Shanghai ports) revealed superior performance across various criteria, emphasizing their prominence in shipping service connectivity, reliability, efficiency, service-related aspects, and transparency of smart port governance. Rotterdam in Europe showed better performance in digitalization and decarbonization initiatives, while the Port of Hong Kong exhibited lower performance than the other four ports, particularly regarding decarbonization management and policy. These insights highlight the importance of strategic decision-making for the port to address specific challenges and capitalize on emerging opportunities.

This paper offered managerial insights into addressing the current focal issue of the impact of the CDD on the port industry, which are the core characteristics of the 6GP model. The perspectives of four major port stakeholder groups were considered. Table 3 lists the relative importance of the 6GP criteria, highlighting the differentiated priorities and strategic focuses among the different stakeholder groups. The performance evaluation results listed in Tables 4–6 and the detailed test results in Appendix Tables 1 and 2 provide decision-makers with a holistic and evidence-based view of port development strategies. These results enable port authorities and terminal operators to understand their performance positioning and identify the key areas for improvement. In the post-pandemic era, this evaluation framework has allowed decision-makers to prioritize the needs of different port users and efficiently allocate limited resources to enhance overall port competitiveness.

The contributions of this study are threefold:

- i) Theoretically, this study extends Port Devolution Theory by incorporating the emerging factors of CDD (COVID-19, digitalisation, and decarbonisation) into the 6GP model, addressing gaps in the literature on port devolution and evolution. Through empirical validation of the 6GP model, this research expands prior work on Chinese ports (Song et al., 2024) to a global scope. By applying the 6GP framework to both Asian and European ports, the study contributes to a comparative understanding of the 6GP model with smart ports, offering insights into its global applicability and the development of sustainable future ports under the 6GP model;
- ii) Methodologically, it introduces a novel hybrid framework (CFPR–MOORA–VIKOR), improving the efficiency, reliability, and applicability of multi-criteria decision-making in maritime studies. The integration of these methods provides dual validation of results and complements the limitations of single-method approaches, reducing data requirements and enhancing computational efficiency;
- iii) Empirically and managerially, it provides a comparative evaluation of leading global container ports, offering actionable insights for policymakers, port authorities, and shipping companies to strengthen resilience, competitiveness, and sustainability in the post-pandemic era, with strategic recommendations for smart port transformation across regions.

Despite its valuable contributions, this study has limitation. The empirical performance evaluation under the 6GP framework was based on stakeholder perceptions, which, although provided by experienced professionals, remain inherently subjective. Additionally, While this study focuses on leading container ports in Asia and Europe, its findings may not be directly generalisable to smaller ports or to those in other regions. Future research should therefore expand the empirical scope to include a broader set of ports worldwide, in order to further validate the applicability of the 6GP model and the robustness of the proposed hybrid framework. Lastly, the study acknowledges the sensitivity of MCDM-based rankings to method and weight selection. Future research could address these limitations by expanding the dataset, incorporating statistical validation, and including a broader range of ports over a longer time frame to enhance the generalizability and robustness of the findings.

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Appendix

**Table 1 (a) – Port performance results evaluated by sub-method of MOORA:
Ratio system**

Port	Shipping co.		Port authority		Freight forwarder		Port expert		Overall	
	y*	Rank	y*	Rank	y*	Rank	y*	Rank	y*	Rank
Singapore	0.489	1	0.479	2	0.505	2	0.495	1	0.493	1
Shanghai	0.447	2	0.460	3	0.426	3	0.424	3	0.441	3
Busan	0.417	5	0.417	4	0.386	5	0.418	4	0.411	4
Hongkong	0.443	3	0.349	5	0.395	4	0.403	5	0.398	5
Rotterdam	0.433	4	0.506	1	0.506	1	0.485	2	0.484	2

Note: y* represents the overall merit score of each port, calculated using the MOORA Ratio System sub-method by subtracting the sum of weighted non-beneficial criteria from the sum of weighted beneficial criteria. A higher y* value indicates better port performance under the given stakeholder perspective.

**Table 1 (b) – Port performance results evaluated by sub-method of MOORA:
Reference point**

Port	Shipping co.		Port authority		Freight forwarder		Port expert		Overall	
	Max Dev.	Rank	Max Dev.	Rank	Max Dev.	Rank	Max Dev.	Rank	Max Dev.	Rank
Singapore	-0.005	1	-0.011	2	-0.004	2	-0.004	1	-0.004	1
Shanghai	-0.008	2	-0.011	3	-0.012	3	-0.011	5	-0.008	3
Busan	-0.008	4	-0.015	4	-0.014	5	-0.011	3	-0.010	4
Hongkong	-0.008	3	-0.022	5	-0.012	3	-0.011	3	-0.010	5
Rotterdam	-0.011	5	-0.006	1	-0.002	1	-0.006	2	-0.004	2

Table 1 (c) – Port performance results evaluated by sub-method of MOORA: Full multiplicative form

Stakeholder Group: Shipping Companies						Stakeholder Group: Port Authorities						Stakeholder Group: Freight Forwarders					
Criteria	Singapore	Shanghai	Busan	Hongkong	Rotterdam	Criteria	Singapore	Shanghai	Busan	Hongkong	Rotterdam	Criteria	Singapore	Shanghai	Busan	Hongkong	Rotterdam
(A1)	4.38	3.88	3.50	4.25	3.57	(A1)	4.33	4.00	3.67	3.25	4.33	(A1)	4.40	3.20	3.60	3.00	4.20
(A2)	19.14	16.47	12.25	15.94	12.24	(A2)	18.78	19.00	13.44	11.38	18.78	(A2)	19.36	10.88	12.96	9.60	18.48
(B1)	66.99	63.82	35.22	53.79	40.23	(B1)	75.11	80.75	49.30	34.13	87.63	(B1)	77.44	43.52	41.47	30.72	77.62
(B2)	251.22	231.33	114.46	194.99	137.94	(B2)	300.44	343.19	213.62	127.97	408.94	(B2)	356.22	139.26	124.42	98.30	357.03
(C1)	942.08	722.92	386.31	706.82	512.36	(C1)	1101.63	1372.75	640.85	255.94	1363.13	(C1)	1638.63	557.06	398.13	334.23	1570.95
(C2)	3532.79	2349.49	1303.78	2473.88	1756.66	(C2)	4406.52	6177.38	2777.02	831.80	5906.89	(C2)	6882.25	1782.58	1274.02	1002.70	6597.98
(C3)	11923.17	7048.47	3748.37	7112.40	6775.67	(C3)	16157.23	18532.13	8331.07	2079.49	25596.51	(C3)	24776.09	5347.74	3567.26	2807.56	26391.92
(D1)	49183.08	26431.77	12650.76	26671.48	24198.83	(D1)	75400.43	64862.44	24993.22	4678.86	102386.03	(D1)	99104.37	19251.86	11415.22	9545.71	105567.69
(D2)	202880.19	99119.14	42696.30	90016.25	82967.42	(D2)	301601.71	243234.14	74979.67	10527.43	443672.78	(D2)	416238.34	73157.05	36528.70	30546.28	464497.86
(E1)	811520.76	359306.88	138762.98	303804.86	284459.72	(E1)	1206406.85	972936.56	299918.67	34214.14	1922582.05	(E1)	1748201.03	307259.61	131503.31	122185.11	1950891.00
(E2)	3448963.25	1257574.10	485670.43	1063317.00	894016.25	(E2)	6032034.24	4621448.67	1099701.78	128303.04	9612910.27	(E2)	8041724.72	1229038.45	447111.25	488740.43	8583920.40
(E3)	11209130.56	4715902.86	1517720.09	3455780.24	2937481.98	(E3)	18096102.72	15019708.18	3665672.59	416984.89	41655944.49	(E3)	33775243.84	4424538.41	1520178.25	1857213.65	34335681.61
(F1)	43435380.90	15916172.14	4932590.30	12527203.38	9651726.50	(F1)	84448479.34	60078832.73	14662690.37	1355200.90	194394407.64	(F1)	148611072.88	15928338.26	4864570.39	5943083.69	151076999.10
(F2)	168312101.00	49738037.94	17880639.83	42279311.42	33091633.70	(F2)	394092903.59	255335039.12	58650761.48	4404402.91	907173902.30	(F2)	653888720.66	57342017.75	15566625.26	19017867.80	664738796.05
Rank	1	2	5	3	4	Rank	2	3	4	5	1	Rank	2	3	5	4	1

Stakeholder Group: Port Experts

Criteria	Singapore	Shanghai	Busan	Hongkong	Rotterdam
(A1)	4.29	3.00	3.33	3.50	3.83
(A2)	17.76	12.00	12.22	12.83	15.33
(B1)	76.09	42.00	40.74	42.78	69.00
(B2)	315.24	161.00	142.59	149.72	276.00
(C1)	1260.97	536.67	546.60	474.12	1058.00
(C2)	5043.90	1699.44	1913.12	1580.40	4055.67
(C3)	21616.71	6231.30	7652.47	5531.40	18250.50
(D1)	95731.13	24925.19	30609.88	22125.62	76043.75
(D2)	410276.28	87238.15	107134.57	77439.66	304175.00
(E1)	1816937.82	363492.28	428538.27	258132.20	1368787.50
(E2)	8046438.92	1332805.04	1499883.95	903462.71	5247018.75
(E3)	28737281.84	4664817.64	4499651.85	2860965.23	20988075.00
(F1)	123159779.32	17104331.36	15748781.48	9059723.24	87450312.50
(F2)	545421879.86	62715881.66	55120735.19	31709031.35	408101458.33
Rank	1	3	4	5	2

Overall Perspective

Criteria	Singapore	Shanghai	Busan	Hongkong	Rotterdam
(A1)	4.35	3.52	3.53	3.50	3.98
(A2)	18.75	14.43	12.72	12.35	16.10
(B1)	74.01	56.35	41.58	39.86	67.02
(B2)	305.17	210.04	146.38	140.26	279.74
(C1)	1221.95	759.21	490.69	427.51	1068.68
(C2)	4872.51	2679.36	1767.51	1398.30	4220.02
(C3)	18183.45	8484.65	5600.79	4081.29	17608.54
(D1)	78280.85	31499.28	19007.69	13672.31	69281.21
(D2)	325075.20	116547.34	62131.39	42127.82	279929.09
(E1)	1351384.05	465946.54	230662.77	147008.53	1152041.51
(E2)	6175342.47	1854078.94	811164.07	542093.94	4716512.78
(E3)	21646780.83	6535628.27	2607554.49	1825049.60	18416859.44
(F1)	93229334.92	23923122.65	9093846.30	6041674.63	76057244.51
(F2)	404853936.24	87568596.86	32567337.07	20126328.62	326321796.69
Rank	1	3	4	5	2

Author Statement

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