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ENHANCING REGIONAL PORT COMPETITIVENESS AND SUSTAINABILITY: PRIORITISING KEY DETERMINANTS USING THE ANALYTIC HIERARCHY PROCESS (AHP) AND TECHNIQUE FOR ORDER OF PREFERENCE BY SIMILARITY TO IDEAL SOLUTION (TOPSIS)

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ABSTRACT

Port attractiveness is critical in enhancing regional port competitiveness and promoting long-term sustainability amid intensifying global trade and environmental challenges. This study identifies and prioritises the key determinants of port attractiveness using a hybrid Multi-Criteria Decision-Making (MCDM) approach that integrates the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Expert evaluations were used to assess the relative importance of various criteria influencing port competitiveness. The results indicate that green port management (ranked first, weight: 0.4770), external environment (second, weight: 0.2297), and location of hinterland and cargo sources (third, weight: 0.1571) are the most influential determinants. Among the strategic alternatives assessed, geographical location and natural conditions emerged as the top-ranked option for enhancing port attractiveness. These findings provide valuable insights for port authorities, policymakers, and maritime stakeholders to design targeted interventions that strengthen port performance while aligning with sustainability goals. The integrated AHP-TOPSIS framework also serves as a practical decision-support tool for prioritising development initiatives in the maritime sector.

Introduction

Ports are essential facilitators of global commerce and economic advancement, serving as critical hubs in worldwide supply chains. As global maritime trade evolves, ports face mounting pressure to strengthen their competitiveness and sustainability amid technological advancements, environmental constraints, and shifting trade patterns (Notteboom *et al.*, 2022; Cullinane & Haralambides, 2021). In this setting, regional ports must accurately identify and prioritise essential performance factors to sustain viability amid intensifying inter-port rivalry, especially in expanding maritime regions.

Recent studies have emphasised the application of Multi-Criteria Decision-Making (MCDM) methods in maritime and port management to address the complexity of decisions that span economic, environmental, and social dimensions (Alzate *et al.*, 2024; Tirkolaee *et al.*, 2022). Among MCDM approaches, the hybrid Analytic Hierarchy Process (AHP) and

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) stand out for their complementary strengths. AHP provides a systematic means of structuring complex decision problems into hierarchical levels and of capturing expert judgments through pairwise comparisons, thereby integrating subjective knowledge from domain specialists into the model. TOPSIS, on the other hand, excels at ranking alternatives by measuring their relative closeness to ideal and anti-ideal solutions, thereby providing a clear, actionable prioritisation of determinants. Together, AHP and TOPSIS combine the qualitative rigour of expert-driven weighting with the quantitative robustness of ranking analysis, producing results that are both transparent and practically interpretable. This dual advantage makes the hybrid method particularly suitable for port evaluation studies, where trade-offs among economic performance, sustainability, and governance must be carefully balanced.

Existing studies demonstrate the growing utility of AHP-TOPSIS in port-related contexts. For example, Bouraima *et al.* (2020) employed the method for port selection along the Belt and Road Initiative, while Yıldız *et al.* (2022) applied it to terminal competitiveness in the Mediterranean. Sadeghi *et al.* (2022) leveraged the approach in sustainable logistics, and Alzate *et al.* (2024) extended it with fuzzy logic to capture uncertainty in sustainability assessments. These applications highlight the flexibility of AHP-TOPSIS in addressing diverse maritime evaluation challenges.

Nevertheless, a critical gap persists in the existing literature. Most studies disproportionately focus on large hub ports or international container terminals in advanced economies, leaving limited insights into the competitive dynamics of regional ports, particularly those in Southeast Asia. Furthermore, much of the extant research emphasises operational or economic indicators, while sustainability-oriented and governance-related dimensions remain underrepresented (Rahman *et al.*, 2024; Zhou & Suh, 2024). Even when sustainability is considered, it is often confined to environmental measures such as emissions or energy use, without adequately capturing broader socio-economic or institutional contributions. Additionally, there is a notable absence of region-specific frameworks that account for local institutional capacity, community integration, and developmental constraints; factors that are central to the performance of regional ports in developing maritime economies like Malaysia.

To address these gaps, this study develops an integrated AHP-TOPSIS model tailored for evaluating regional ports in Malaysia. By combining expert judgment with quantitative prioritisation, the model incorporates a holistic set of criteria, including economic, environmental, operational, and institutional, while embedding sustainability as a core evaluative dimension rather than a supplementary one. This approach not only addresses the methodological and geographical limitations in current scholarship but also provides actionable insights for policymakers and port authorities seeking data-driven strategies to enhance regional port resilience, competitiveness, and long-term sustainability.

Regional Port Competitiveness and Sustainability

In the evolving landscape of maritime logistics, port competitiveness and sustainability have emerged as interlinked priorities. Ports are no longer evaluated solely on throughput or operational efficiency but are increasingly assessed by their ability to deliver economic value, ensure environmental stewardship, and support regional development. This paradigm shift has encouraged the adoption of multi-dimensional analytical tools, particularly Multi-Criteria Decision-Making (MCDM) techniques that can account for diverse, often conflicting evaluation criteria.

Among these approaches, the hybrid combination of the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) has gained traction. AHP is effective for structuring complex problems into a hierarchy and assigning weights through expert pairwise comparisons, while TOPSIS provides a straightforward ranking mechanism by comparing alternatives against ideal and anti-ideal solutions. When combined, the two methods offer a balanced framework that integrates subjective expertise with objective prioritisation, making them highly suitable for evaluating multi-dimensional port performance, where trade-offs among efficiency, sustainability, and governance must be addressed.

Applications of AHP-TOPSIS in maritime research further strengthen its methodological foundations. For instance, Tirkolaee *et al.* (2022) used the method to advance sustainability-driven supplier selection in logistics, Kabir and Sarker (2023) applied it to evaluate port performance under uncertain geopolitical scenarios, and Bahri *et al.* (2025) examined container terminal efficiency. Similarly, Alzate *et al.* (2024) extended the framework with fuzzy logic to better handle uncertainty, while Bouraima *et al.* (2020) demonstrated its adaptability in port selection across Belt and Road economies. These studies collectively underscore the versatility of AHP-TOPSIS in addressing diverse port management challenges.

Yet, despite its growing use, key gaps remain. Most prior research emphasises large hub ports or container terminals in advanced maritime economies, leaving regional ports, especially in Southeast Asia, underexplored. Studies such as Yıldız *et al.* (2022) highlight competitiveness in the Mediterranean but overlook factors specific to regional ports, including community integration, local economic linkages, and institutional governance. Likewise, while sustainability is increasingly acknowledged, it is often narrowly defined as environmental performance (e.g., emissions, energy consumption), neglecting broader socio-economic and governance dimensions that are critical to regional port development (Rahman *et al.*, 2024; Zhou & Suh, 2024).

To address these shortcomings, this study develops an integrated AHP-TOPSIS framework specifically designed for regional ports in Malaysia. By embedding sustainability as a central evaluative pillar and incorporating economic, operational, environmental, and institutional dimensions, the model addresses both methodological and contextual gaps in the existing literature. In doing so, it contributes a region-specific, decision-support tool that can guide policymakers and port authorities in strengthening regional competitiveness and ensuring long-term resilience.

Materials and Methods

This study employs a hybrid Multi-Criteria Decision-Making (MCDM) approach combining the Cause-and-Effect Analysis (CEA), Analytic Hierarchy Process (AHP), and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to identify and prioritise the key determinants influencing regional port competitiveness and sustainability in Malaysia. This hybrid methodology enabled a robust evaluation of port-attractiveness determinants and facilitated the ranking of strategic port-development alternatives.

To ensure the robustness and credibility of the data, a purposive sampling method was used to select respondents with relevant expertise in port operations, maritime policy, logistics, and sustainability. A total of 15 experts were invited to participate in the study, out of which 12 completed all stages of the data collection process, yielding a valid response rate of 80%.

The selected experts were drawn from diverse but relevant backgrounds to provide a balanced perspective, including five port authority officers with experience in regional port development and operations, three maritime logistics professionals from the private sector, government officials involved in maritime policy and regulatory affairs, and two academic researchers specialising in maritime transport and sustainability. This multidisciplinary composition ensured comprehensive insights into port efficiency, logistics, policy frameworks, and sustainable practices.

Each expert had at least 10 years of professional experience in their respective fields, and several had contributed to national or regional port development initiatives. This sample size exceeds the minimum threshold for AHP studies, which typically recommend 10 to 15 experts to ensure consistency and avoid overcomplication (Pant, Kumar, Ram, Klochkov & Sharma, 2022).

Data were collected through a combination of semi-structured interviews and structured AHP pairwise-comparison questionnaires, conducted face-to-face or via virtual meetings, depending on participant availability. The interview process aimed to validate the initial set of criteria derived from the literature and to gather in-depth insights into the contextual challenges of regional ports in Malaysia.

The study uses Cause and Effect Analysis (CEA) to discover and assess the root causes of port attractiveness. The study identifies the characteristics that have the greatest impact on port performance by examining causal links informed by expert perspectives, empirical data, and industry benchmarks.

Meanwhile, the AHP method was used to structure the decision problem hierarchically (Figure 1) and to derive weights for the identified criteria. Experts were asked to perform pairwise comparisons of the criteria using a 9-point Saaty scale, where 1 represents equal importance and 9 indicates extreme importance of one element over another. The geometric mean was used to aggregate the individual judgments into a group matrix.

To verify the consistency of the comparisons, the Consistency Ratio (CR) was calculated for each respondent. Only judgments with a CR ≤ 0.10 were accepted; otherwise, participants were asked to revise their inputs. The final criterion weights were then normalised for use in the TOPSIS analysis.

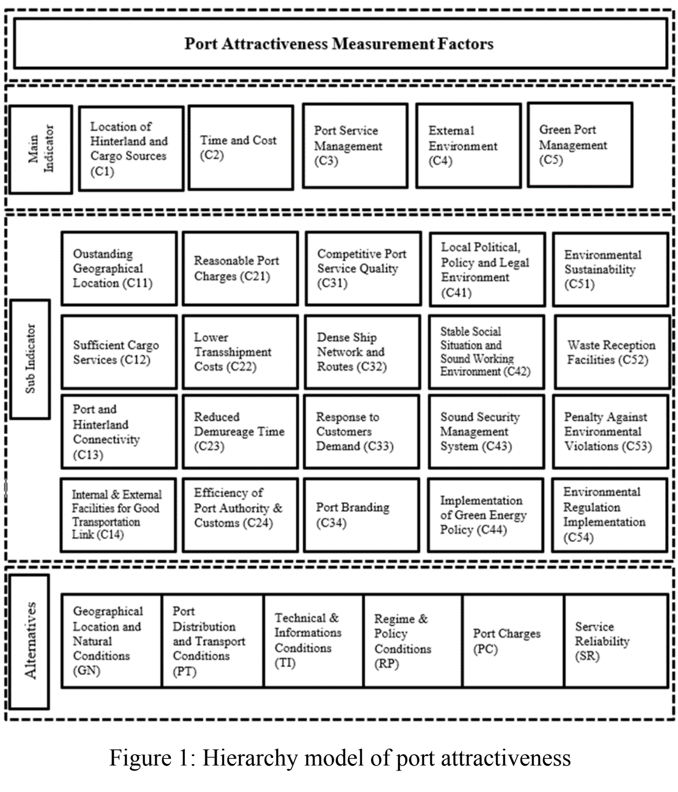

Figure 1: Hierarchy model of port attractiveness

The Analytic Hierarchy Process (AHP) is a widely used Multiple-Criteria Decision-Making (MCDM) tool for ranking decision options based on multiple criteria (Taherdoost & Madanchian, 2023). It helps decision-makers prioritise alternatives by structuring complex problems into a hierarchy and assigning weights to different factors. AHP has been applied across various fields, including sustainable energy (selecting renewable power sources) (Zaheb *et al.*, 2024), food waste management (evaluating alternatives like composting) (Mathioudakis *et al.*, 2022), and the hospitality industry (using topic modelling to rank hotels/restaurants) (Fang & Partovi, 2021). In transportation, AHP is frequently used to evaluate transport options, with a systematic review (2003–2022) highlighting its role in public transport and logistics, often in combination with TOPSIS (Moslem *et al.*, 2023). The steps in the AHP method included:

Step 1: Create a pairwise comparison matrix using the Saaty scale (Table 1). In this matrix, the diagonal elements are set to 1 to represent self-comparisons, and the values in the lower left are the inverses of those in the upper right. To store pairwise comparisons between attributes, let A $= [a_{ij}]_{n\times n}$, where $a_{ij} = {}^{1}/_{a_{ij}}$.

Table 1: Scale of relative importance

Scale of Importance	Numeric Ratings
Equally important	1
Weakly important	3
Strongly important	5
Very strongly important	7
Extremely important	9
Intermediate values between the two adjacent judgments	2, 4, 6, 8

Step 2: Calculate the geometric mean for each row of the pairwise comparison matrix to determine the criteria weights.

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{akj}{\Sigma_{J=1}^{n}\ aij}\right)(k = 1,2,3\ldots,n) \quad (1)$$

Step 3: Calculate the maximal eigenvalue (λmax) of the comparison matrix, which should equal the number of factors in the comparison (n).

$$\lambda max = \Sigma_{j=1}^{n}\left(\frac{\sum_{k=1}^{n} W_{ka_jk}}{Wj}\right)Wj \quad (2)$$

Step 4: Determine the Consistency Index (CI) using Equation (3):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (3)$$

Step 5: Calculate the Consistency Ratio (CR) by comparing the CI to a maximum value of 0.10. If the CR is less than 0.10, the AHP demonstrates an acceptable level of consistency. Nevertheless, the ratio is inconsistent if the CR is greater than 0.10.

$$\mathrm{CI} = \frac{\lambda_{\max} - \mathrm{n}}{\mathrm{n} - 1} \quad (4)$$

with Random Index (RI) as shown in Table 2.

Table 2: Value of average random index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.6	1	1.1	1.2	1.3	1.4	1.45	1.49

Once the criterion weights were established through AHP, the TOPSIS method was employed to rank the identified strategic alternatives for regional port development. Experts were asked to score each alternative (e.g., geographical location and natural conditions, port distributions and transport conditions, technical and information conditions, regime and policy conditions, port charges, and service reliability) against the criteria using a Likert scale from 1 (not all effective) to 5 (extremely effective). The steps in the TOPSIS method included:

Step 1: Normalise the decision matrix. In this step, the decision matrix is normalised to make scores obtained on different scales comparable. The normalised value r_ij is calculated by using Equation (5):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x^2{}_{ij}}} \quad , i = 1,2,\dots,m; j = 1,2,\dots,n \qquad (5)$$

Step 2: Calculate the weighted normalised decision matrix. The weighted normalised matrix is obtained by multiplying each column of the normalised decision matrix by the associated criteria weight for that column. The weighted normalised value is calculated by using Equation (6):

$$V_{ij} = W_j \times R_{ij}, \quad i = 1,2,\dots,m; \quad j = 1,2,\dots,n \qquad (6)$$

where, W_j represents the weight of the j^{th} criterion and $\sum_{i=1}^{n} W_j = 1$.

Step 3: Determine the Positive Ideal Solutions (PIS) and Negative Ideal Solutions (NIS) by producing the positive ideal solutions (S_i^+) and negative ideal solutions (S_i^-) in the following.

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right]^{0.5} \qquad (7)$$

Step 4: Calculate the PIS and NIS.

$$S_i^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right]^{0.5} \qquad (8)$$

Step 5: Calculate the performance score and ranking. Each alternative's relative process (Pi) value is determined using Equation (9). The value of (Pi) lies between 0 and 1.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \qquad (9)$$

Results and Discussions

Figure 2 shows that Green Port Management (Weight: 0.4770) is the most important component, highlighting the maritime industry's growing focus on environmentally friendly operations. This includes energy efficiency, waste reduction, and emissions control, which are increasingly driven by global regulations such as IMO 2020, ESG frameworks, and stakeholder demands for greener logistics. The prioritisation of this factor signals that environmental stewardship has become a core competitive advantage rather than a supplementary consideration.

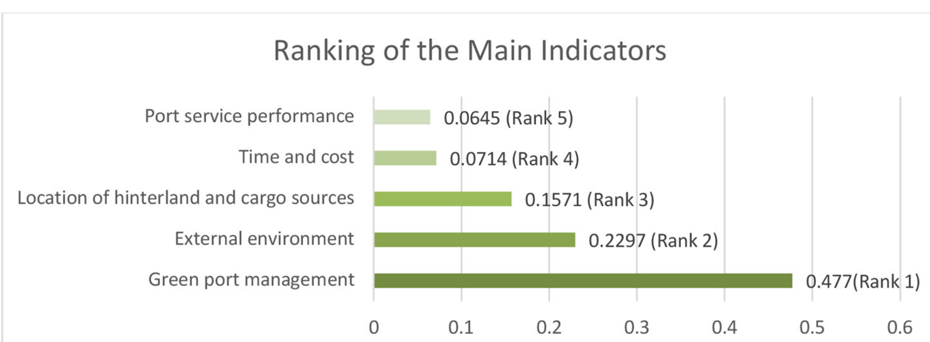

Figure 2: Ranking of the main indicator

This was followed by External Environment (0.2297) and Location of Hinterland and Cargo Sources (0.1571), while Time and Cost Efficiency (0.0714) and Port Service Performance (0.0645) ranked lowest. Meanwhile, the subindicator level (Table 3) shows the top five priorities were Implementation of Green Energy Policy, Port Branding, Penalty Against Environmental Violations, Outstanding Geographical Location, and Waste Reception Facilities, reflecting a strong emphasis on environmental performance and strategic positioning. Competitive Port Service Quality ranked lowest, indicating it is perceived as a baseline expectation rather than a differentiating factor.

Table 3: Ranking for the subindicator

Subindicator	Global Weight	Ranking
Implementation of green energy policy	0.4710	1
Port branding	0.3414	2
Penalty against environmental violations	0.3346	3
Outstanding geographical location	0.3288	4
Waste reception facilities	0.3108	5
Efficiency of the port authority and customs	0.3049	6
Lower transhipment cost	0.2829	7
Dense ship network and routes	0.2725	8
Internal and external facilities for a good transportation link	0.2543	9
Response to customers' demand	0.2436	10
Sufficient cargo sources	0.2379	11
Reasonable port charges	0.2260	12
Reduced demurrage time	0.1861	13
Local political, policy, and legal environment	0.1802	14
Environmental regulation implementation	0.1800	15
Stable social situation and sound working environment	0.1791	16
Port and hinterland connectivity	0.1788	17
Environmental sustainability	0.1744	18
Sound security management system	0.1694	19
Competitive port service quality	0.1423	20

Building on the AHP-derived weights, the TOPSIS method ranked six strategic alternatives for port development, providing policymakers and port authorities with actionable insights. Table 5 shows that Geographical Location & Natural Conditions (CC: 0.6391, Rank 1) is the highest-ranked alternative, highlighting the critical importance of strategic location and natural advantages like deep-water access or proximity to major shipping lanes. This finding suggests that while other factors can be optimised, geographical endowments remain a foundational driver of port attractiveness. Next, followed closely by Technical and Information Conditions, and Port Distribution and Transport Conditions. Service Reliability, Regime and Policy Conditions, and Port Charges were ranked lower, suggesting that while these factors remain relevant, they are secondary to sustainability, location advantages, and technological readiness.

These results are broadly consistent with recent literature. For instance, Ma *et al.* (2023) and Fazi *et al.* (2022) both emphasised infrastructure and digital capabilities as central to port competitiveness amid automation, trade disruptions, and rising customer expectations. The ranking of digitalisation as a key determinant in this study aligns with findings by Tirkolaee *et al.* (2022), who argued that digital tools such as smart port systems and blockchain integration are rapidly becoming essential for operational efficiency and service differentiation, even for small- and medium-sized ports.

Moreover, the prioritisation of environmental compliance reflects a growing shift in the maritime sector toward green and sustainable practices. Recent studies (Sun *et al.*, 2023; Zhou *et al.*, 2023) have highlighted how regulatory pressure, stakeholder expectations, and international conventions such as IMO 2020 are pushing ports to invest in green infrastructure and adopt sustainability performance indicators. In this context, the current study advances the field by demonstrating that sustainability is no longer peripheral even for regional ports but has become integral to long-term competitiveness.

Interestingly, policy and regulatory support emerged as a higher priority than commonly reported in past studies on larger hub ports. This finding suggests that regional ports, which often operate with limited institutional autonomy, are more dependent on centralised government strategies, subsidies, and maritime policy reforms. Rahman *et al.* (2022) similarly observed that decentralised governance and regulatory fragmentation can hinder smaller ports from achieving competitiveness, especially in developing countries. The emphasis on governance in this study thus contributes a novel regional perspective that has been underexplored in global port competitiveness frameworks.

The recognition of human capital development as a top-tier factor also resonates with findings by Kabir and Sarker (2023), who noted that skill shortages, resistance to digital transformation, and lack of training are persistent barriers to innovation in port operations. For regional ports aiming to modernise, human resource capabilities remain a critical enabler for sustaining change and absorbing technological advancements.

Beyond confirming known factors, this study contributes new insights by integrating both competitiveness and sustainability into a unified prioritisation model. While past studies often treat these themes in isolation, our findings demonstrate that the two are increasingly interdependent. For example, infrastructure improvements without environmental consideration may yield short-term efficiency but fail to meet long-term regulatory or societal expectations.

In sum, this research provides a contextualised, evidence-based framework for prioritising development strategies in regional ports. By engaging a diverse panel of experts and applying a hybrid AHP-TOPSIS model, the study offers a replicable and adaptable tool for strategic planning that policymakers and port authorities can use. It also broadens the academic discourse by incorporating underrepresented regional voices and emphasising the holistic nature of modern port development.

Conclusions

This study contributes to the growing body of research on regional port competitiveness and sustainability by offering both theoretical and practical insights. From a scholarly perspective, it advances the literature on Multi-Criteria Decision-Making (MCDM) in maritime studies by integrating AHP and TOPSIS in a regional port context that has been largely underexplored, particularly in Southeast Asia. Whereas much of the existing research has concentrated on large hub ports or emphasised operational and economic factors, this study broadens the analytical lens to include institutional and sustainability-oriented dimensions. In doing so, it enriches the theoretical dialogue on how port performance can be evaluated through a more holistic, multi-dimensional framework.

The knowledge contributions of this study are threefold. First, it extends the application of hybrid MCDM methods to the evaluation of regional ports, a domain that has received less scholarly attention than hub ports. Second, it embeds sustainability as a core evaluative dimension, systematically incorporating economic, operational, environmental, and institutional factors within a unified framework. Third, it highlights governance and socio-economic linkages as critical, yet often overlooked, determinants of port competitiveness.

Meanwhile, the novelty of this research lies in its regional focus, methodological design, and evaluative scope. Unlike previous studies that concentrated on container terminals or efficiency-based metrics, this study develops a context-sensitive framework tailored to Malaysian regional ports. It differs by treating sustainability not as an add-on but as an integral component of competitiveness, and by demonstrating how expert judgment and quantitative prioritisation can be effectively combined to generate results that are both methodologically rigorous and practically interpretable. This methodological and contextual integration distinguishes the study from prior research that often overlooked regional realities and broader sustainability imperatives.

In practice, the proposed model provides policymakers and port authorities with a robust decision-support tool for resource allocation, strategic planning, and alignment with sustainability objectives. By identifying and ranking critical determinants of competitiveness, the study equips regional ports with actionable insights to strengthen resilience and adapt to evolving market and regulatory pressures.

Looking ahead, future research could extend the application of this framework to other regional contexts or employ dynamic weighting and fuzzy extensions to capture evolving priorities under conditions of uncertainty. Ultimately, this study not only addresses methodological and geographical gaps in the literature but also underscores the importance of evidence-based, sustainability-driven planning in shaping resilient, competitive, and future-ready port systems. The significance of this study lies in its contribution to the ongoing discourse on regional port revitalisation, particularly in emerging economies such as Malaysia, where smaller ports face distinct institutional and operational challenges. The integration of expert assessment with analytical rigour ensures that the proposed framework remains both contextually relevant and adaptable. Notably, the findings address a gap in the literature by simultaneously considering competitiveness and sustainability, which are frequently examined in isolation. The proposed model can serve as a practical tool for policymakers and port managers to allocate resources effectively, align strategies with broader environmental goals, and respond to shifting market and regulatory dynamics.

Future research could expand the model across different regions or incorporate dynamic weighting methods to reflect changing priorities over time. Ultimately, this study underscores the need for evidence-based planning in the maritime sector and contributes to shaping more resilient, inclusive, and future-ready port systems.

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Conflict of Interest Statement

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

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