A Multi-Criteria Sustainability Framework for Seaport Site Selection: Integrating the Triple Bottom Line and Analytic Hierarchy Process

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A Multi-Criteria Sustainability Framework for Seaport Site Selection: Integrating the Triple Bottom Line and Analytic Hierarchy Process

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Abstract: *The rapid growth of global trade has increased demand for sustainable and strategically located seaports. In the Philippine context, inefficient site selection contributes to logistical inefficiencies, environmental harm, and community opposition. This study presents a structured decision-making framework for sustainable seaport site selection by integrating the Triple Bottom Line (TBL) approach with the Analytic Hierarchy Process (AHP). Four key sub-criteria—cost efficiency, stakeholder acceptance, accessibility, and resilience—were prioritized using expert-based pairwise comparisons. Results showed that environmental sustainability was the most important criterion (46.77%), followed by social (33.00%) and economic factors (20.23%). Cost efficiency (33.45%) ranked highest among sub-criteria. A Circular Policy Feedback Model was developed to illustrate the interdependence of economic, environmental, social, and logistical domains, promoting adaptive and inclusive policy development. This framework provides a replicable tool for planners and decision-makers, emphasizing the need to move beyond cost-centric planning toward integrated and sustainable infrastructure strategies.*

Keywords: Sustainable Seaport Development, Seaport Site Selection, Triple Bottom Line (TBL), Analytic Hierarchy Process (AHP), Multi-Criteria Decision-Making (MCDM)

1. INTRODUCTION

The global surge in trade has amplified the strategic importance of container seaports as economic gateways. Modern ports must address not only increasing cargo demands but also sustainability challenges, necessitating the integration of environmental, economic, and social considerations in site selection. Poorly located seaports contribute to inefficiencies, ecological damage, and public opposition, especially in archipelagic countries like the Philippines. To address these issues, this study integrates the Triple Bottom Line (TBL) framework with the Analytic Hierarchy Process (AHP) to develop a structured, multi-criteria decision-making model for sustainable seaport site selection. The goal is to provide a transparent, adaptable, and evidence-based framework that balances cost efficiency, accessibility, resilience, and stakeholder acceptance.

1.1 Background of the Study

Seaports serve as vital infrastructure for global trade, handling over 80% of the world's goods by volume [1]. As trade volumes increase and climate-related challenges intensify, the demand for sustainable and strategically located port facilities is more critical than ever. In archipelagic countries like the Philippines, efficient port operations are central to national connectivity and economic development. However, site selection for new container ports continues to be marred by inefficiencies, poor planning, and limited stakeholder engagement.

The Philippines faces persistent issues in seaport planning, including congestion in Metro Manila ports, inadequate hinterland connectivity, and environmental degradation in coastal areas. Ports such as Manila and Batangas have experienced challenges related to accessibility, local resistance, and underdeveloped infrastructure, highlighting a lack of integrated planning frameworks [2]. Furthermore, the intensifying impacts of climate change such as rising sea levels and increased storm frequency pose long-term risks to coastal infrastructure [3].

There is a pressing need for a decision-making framework that accounts for the Triple Bottom Line (TBL) economic, environmental, and social sustainability. Traditional cost-centric approaches do not adequately reflect the complexity of port planning in a modern context. Infrastructure must not only be financially viable but also socially inclusive and environmentally resilient [5].

Key decision variables such as cost efficiency, accessibility, resilience, and stakeholder acceptance are often acknowledged in literature, yet rarely integrated into a holistic decision model. In the Philippine context, there is a notable gap in applying structured, data-driven methodologies that can evaluate and prioritize port locations based on multiple sustainability criteria.

While the Analytic Hierarchy Process (AHP) has been widely applied in infrastructure and urban planning [6], most existing models either ignore TBL dimensions or focus on isolated variables like cost or environmental impact [7], [8]. Furthermore, current applications often lack adaptability to dynamic policy and climate conditions, as noted by Cruz et al., who emphasized the limitations of traditional planning in addressing stakeholder diversity and logistics complexity [9].

There is a clear research gap in integrating AHP with TBL principles for seaport site selection in a developing country context. Specifically, few frameworks have been tailored to the unique geographic and socio-political landscape of the Philippines, where stakeholder dynamics, vulnerability to climate change, and regional disparities add further layers of complexity.

This study addresses these gaps by developing a sustainability-driven site selection framework that integrates TBL and AHP. By incorporating expert-based evaluations across cost, accessibility, resilience, and stakeholder acceptance, the research aims to support evidence-based, adaptive, and socially responsive infrastructure planning. The resulting framework will serve as a practical tool for planners, policymakers, and port authorities seeking to align port development with long-term national development goals and international sustainability standards.

2. MATERIALS AND METHODOLOGY

2.1 Theoretical Framework

This study is grounded in two interrelated theoretical frameworks: the Triple Bottom Line (TBL) and the Analytic Hierarchy Process (AHP). Together, they provide a systematic and sustainability-oriented approach to decision-making in seaport site selection.

2.1.1 Triple Bottom Line (TBL) Framework

The TBL framework as shown in Figure 1.0, introduced by Elkington, emphasizes the need for sustainable development that balances three interconnected pillars: economic viability, environmental protection, and social equity [10]. In the context of seaport development, TBL offers a holistic lens for evaluating potential sites by ensuring that financial costs, ecological impacts, and community concerns are equally considered. This approach helps bridge the traditional gap between economic feasibility and social-environmental responsibility [11].
For infrastructure projects like seaports—particularly in climate-vulnerable countries such as the Philippines—TBL has become increasingly relevant. Ports must not only generate revenue but also mitigate ecological degradation and foster community support. As recent literature shows, applying the TBL framework ensures that sustainability considerations are integrated from the earliest planning stages [12].

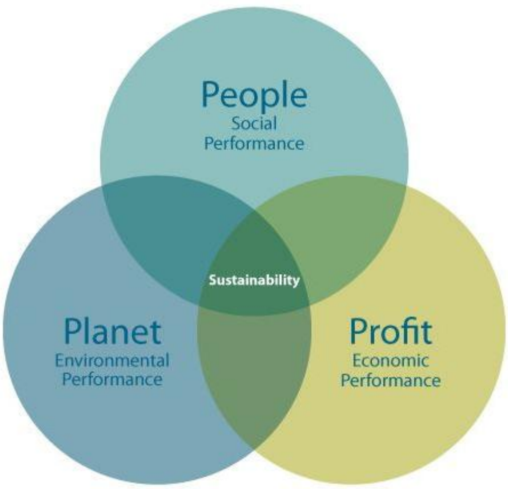

Fig. 1. Triple Bottom Line Model.

2.1.2 Analytic Hierarchy Process (AHP)

TDeveloped by Thomas Saaty, AHP is a structured, multi-criteria decision-making (MCDM) method that decomposes complex decisions into a hierarchy of goals, criteria, and alternatives [13]. Through pairwise comparisons, AHP calculates the relative importance of each criterion, allowing for transparent and rational prioritization. In this study, AHP is employed to evaluate key sub-criteria for seaport site selection: cost efficiency, accessibility, resilience, and stakeholder acceptance.

AHP's strength lies in its ability to incorporate both qualitative and quantitative factors into a consistent decision model. This is especially useful in infrastructure planning, where data can be limited, and stakeholder judgments are critical [14]. Prior research has validated the method's utility in urban planning, coastal tourism, and hospital site selection [15], [16].

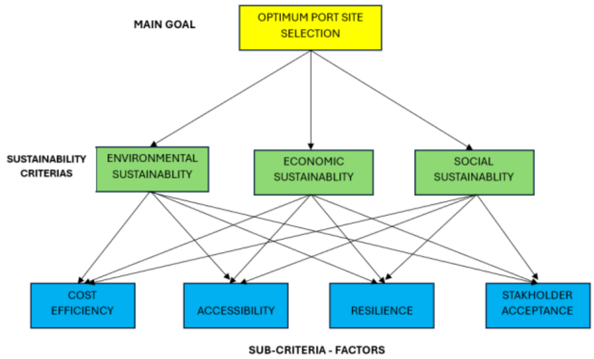

Fig. 2. Analytical Hierarchy Process Model

2.1.3 Related Studies

The process of selecting seaport sites is a complex, multi-dimensional challenge that continues to face critical issues globally. In many countries, poorly planned port locations have led to environmental degradation, community displacement, traffic congestion, and underutilized infrastructure. For example, studies in Indonesia have shown that neglecting social factors in port development projects often results in resistance from local communities and delayed implementation [18]. Similarly, research in Vietnam has highlighted how weak coordination between port planning and urban development can lead to logistical bottlenecks and fragmented hinterland connectivity [19].
To address these issues, researchers have increasingly turned to structured decision-making methods like the Analytic Hierarchy Process (AHP). Saka and Çetin [20] proposed an AHP-based optimization model for selecting dry port locations in Turkey, noting the importance of including both quantitative and qualitative factors such as accessibility and environmental impact. In South Korea, Yeo et al. [21] used AHP to identify seaport competitiveness drivers and emphasized that stakeholder perspectives are critical to sustainable port performance. Similarly, Serafim et al. [22] applied AHP to evaluate coastal protection structures in Brazil, underlining the value of balancing technical, ecological, and social criteria. Lirn et al. [23] conducted a global assessment of transshipment port selection and found that ignoring long-term environmental risks could undermine economic gains.
Urban infrastructure planning has also benefited from AHP, as shown by Yang et al. [24], who employed the method to prioritize green infrastructure projects based on sustainability principles. This multidimensional approach has proven particularly valuable in regions where environmental vulnerabilities and rapid urbanization co-exist.
Relevant insights have also emerged from the studies of Yi and Eljamal [25] were they reviewed the application of nanomaterials in water treatment and emphasized the need for structured decision-making frameworks like AHP to evaluate complex infrastructure interventions.

Khalil and Eljamal [26] demonstrated how geotechnical decision-making in port-related projects can be enhanced by integrating stakeholder and environmental assessments, a principle that aligns with Triple Bottom Line (TBL) sustainability.

These studies collectively show that site selection problems in seaport infrastructure often stem from fragmented planning approaches that overlook social and environmental dimensions. AHP, particularly when integrated with TBL, offers a systematic, replicable framework that can bridge these gaps and guide sustainable, stakeholder-driven seaport development.

2.2 Methodology

2.2.1. Research Design

This study employed a quantitative, descriptive research design integrated with the Analytic Hierarchy Process (AHP) framework. The primary objective was to develop a structured decision-making model for sustainable seaport site selection in the Philippine context. The design was grounded in the Triple Bottom Line (TBL) framework, encompassing environmental, social, and economic sustainability dimensions. AHP was selected due to its strength in multi-criteria decision analysis, particularly in infrastructure planning problems where both qualitative and quantitative variables must be systematically evaluated [13]. The integration of TBL and AHP provided a coherent methodological foundation to ensure that sustainability considerations were embedded in each stage of the decision-making process.

2.2.2 Sampling Method

The study employed purposive expert sampling, targeting professionals with substantial expertise in port development, environmental planning, and infrastructure policy. A total of 12 experts were selected based on the following qualifications: a minimum of five years of professional or academic experience in port planning, logistics, civil engineering, or environmental management; active involvement in port development projects within the Philippines or comparable contexts; and possession of postgraduate academic credentials in relevant fields. This approach aligns with best practices in AHP studies, which prioritize the quality of expert judgment over sample size [14].

The selection criteria for respondents are consistent with the framework proposed by Amora and Juanzon, who emphasize the importance of including technical experts, policymakers, and planners with both practical experience and conceptual understanding of infrastructure systems in multi-criteria decision analyses [27]. Each expert was provided with a structured AHP questionnaire to perform pairwise comparisons of identified criteria and sub-criteria. Participants received a briefing on the AHP methodology and utilized Saaty's standardized 9-point scale for their evaluations [13].

2.2.3. Analytical Procedure

Following data collection, the study followed the standard AHP methodology for decision modeling. The process involved constructing a hierarchical structure comprising three levels: the overall goal (sustainable seaport site selection), the main criteria (TBL dimensions), and the sub-criteria derived from a review of relevant literature. Pairwise comparison matrices were generated from expert input, and the principal eigenvector method was applied to compute the relative weights of criteria and sub-criteria. To ensure the reliability of expert judgments, Consistency Ratios (CR) were calculated for each matrix. A CR value below the 0.10 threshold was considered acceptable, indicating consistency in pairwise comparisons [13]. All computations were performed using Microsoft Excel and AHP calculation templates validated in previous multi-criteria decision-making studies [21].

3. RESULTS AND DISCUSSION

3.1 Experts Respondents' Profile

A total of twelve (12) qualified experts participated in the AHP survey. All respondents satisfied the criteria for expert judgment in AHP, particularly having more than 10 years of relevant professional experience in construction project management and infrastructure planning in seaports. The diverse professional roles and extensive experience of the panel ensured that the responses were well-informed and reflective of real-world practices in seaport development and infrastructure planning.

3.2 AHP Prioritization of Sustainability Criteria

Using AHP pairwise comparison, expert evaluations ranked the three major criteria under the TBL framework. The results are shown in Table 1.0.

Table 1. Comprehensive List of Critical Success Factors

Normalized Criteria	1	2	3	Weights	Ranking
Environmental	1.00	2.42	1.36	**46.77%**	**1**
Social	0.41	1.00	0.64	**20.23%**	**2**
Economic	0.74	1.56	1.00	**33.00%**	**3**
Eigenvalue (γ_{max})			**3.002**		
Random Consistency Index (RI)			**0.58**		
Consistency Index (CI)			**0.0058**		
CONSISTENCY RATIO (CR)			**0.205%**		

The AHP results revealed that Environmental Sustainability holds the highest priority in seaport site selection, with a computed weight of 46.77%. This emphasizes the increasing importance of ecological preservation in coastal infrastructure planning. The finding supports existing literature that highlights the environmental risks associated with seaport operations, including threats to marine biodiversity, air and water pollution, and rising carbon emissions [28], [29]. This growing concern aligns with global efforts to integrate ecological stewardship in large-scale infrastructure development.

Social Sustainability ranked second with a weight of 33.00%, highlighting the significance of stakeholder inclusion, community well-being, and equitable access in decision-making processes. This supports the findings of Satria and Gabriel, who stressed that community empowerment is essential for socially sustainable infrastructure projects [30]. The ranking reflects a recognition that inclusive planning contributes to long-term project success and public acceptance.

Economic Sustainability, though still important, received the lowest priority weight at 20.23%. This suggests a shift in stakeholder preferences from purely financial feasibility toward more balanced and holistic planning approaches. The result aligns with Hiranandani's assertion that infrastructure projects must "go beyond cost" and integrate broader social and environmental objectives [31].

The Consistency Ratio (CR) of the pairwise comparison matrix for the main criteria was calculated at 0.21%, well below the AHP threshold of 10%. This indicates that the expert evaluations were logically consistent and the resulting priority weights are statistically valid. Thus, the study can proceed with confidence in using these weights for policy modeling and sustainability-based site selection frameworks.

3.3 Evaluation of Alternatives under each Sustainability Dimension

The following tables present the results of AHP evaluations of the four sub-criteria—cost efficiency, accessibility, resilience, and stakeholder acceptance—in relation to each TBL dimension.

3.3.1 With Respect to Environmental Sustainability

Table 2 below shows the normalized ranking of the sub-criteria with respect to environmental sustainability.

Table 2. Alternatives Rankings – Environmental Sustainability

	NORMALIZED					
CRITERIA	1	2	3	4	WEIGHTS	RANKING
1	1.00	1.25	1.86	0.99	**29.73%**	**2**
2	0.79	1.00	1.34	0.66	**22.04%**	**3**
3	0.54	0.75	1.00	0.47	**15.84%**	**4**
4	1.01	1.52	2.13	1.00	**32.38%**	**1**
Eigenvalue (γ_{max})					**4.004**	
Random Consistency Index (RI)					**0.90**	
Consistency Index (CI)					**0.00538**	
CONSISTENCY RATIO (CR)					**0.1479%**	

Within the environmental sustainability dimension, Stakeholder Acceptance emerged as the most influential sub-criterion, receiving a priority weight of 32.38%. This highlights the pivotal role of local communities, environmental advocacy groups, and regulatory bodies in determining the environmental outcomes of seaport projects. The result confirms prior studies that emphasized stakeholder consultation as essential for promoting environmentally responsible and socially acceptable infrastructure planning [32], [33].

Cost Efficiency, with a weight of 29.73%, ranked second, indicating that while ecological concerns dominate, economic pragmatism remains a necessary complement in seaport planning. The presence of cost considerations within the environmental dimension suggests an effort to balance ecological safeguards with financial feasibility—a common theme in sustainable infrastructure literature.

The sub-criteria Accessibility (22.04%) and Resilience (15.84%) were rated lower in terms of environmental sustainability. This may be attributed to their stronger associations with operational performance rather than direct environmental impacts, thereby receiving less emphasis in ecological prioritization.

The Consistency Ratio (CR) for the main criteria matrix was calculated at 0.15%, significantly below the AHP acceptability threshold of 10%, demonstrating strong consistency in expert evaluations. Likewise, the CR for the environmental sub-criteria matrix was also 0.15%, confirming the logical coherence and reliability of the expert responses at this level. These low CR values validate the robustness of the prioritization results, ensuring their suitability for guiding evidence-based environmental policy formulation in seaport development.

3.3.2. With Respect to Economic Sustainability

Table 3 below shows the normalized ranking of the sub-criteria with respect to environmental sustainability.

Table 3. Alternative Rankings – Economic Sustainability

	NORMALIZED					
CRITERIA	1	2	3	4	WEIGHTS	RANKING
1	1.00	2.55	2.70	2.50	**46.03%**	**1**
2	0.39	1.00	0.87	0.65	**15.46%**	**4**
3	0.37	1.15	1.00	0.68	**16.51%**	**3**
4	0.39	1.54	1.46	1.00	**21.99%**	**2**
Eigenvalue (γ_{max})					**4.020**	
Random Consistency Index (RI)					**0.90**	
Consistency Index (CI)					**0.02614**	
CONSISTENCY RATIO (CR)					**0.7200%**	

In the economic sustainability dimension, Cost Efficiency was identified as the most significant sub-criterion, with a priority weight of 46.03%. This underscores the prevailing emphasis among industry experts on minimizing capital investment and operational expenses in seaport planning and development. The finding aligns with early port planning principles by Gaither and Sides, who emphasized that financial viability is a foundational element in port site selection decisions [34].

Surprisingly, Stakeholder Acceptance ranked second with 21.99%, reflecting the growing recognition that economic outcomes are increasingly influenced by social dynamics. Public resistance, litigation, and project delays stemming from poor stakeholder engagement can result in substantial cost overruns. This finding reinforces the notion that economic viability is not solely driven by technical and financial metrics but also by public perception and political feasibility.

Resilience (16.51%) and Accessibility (15.46%) were ranked lower, indicating their more supportive role in economic sustainability. While both contribute to long-term operational stability and regional connectivity, they are viewed as secondary to immediate cost concerns in economic evaluations.

The Consistency Ratio (CR) for this set of pairwise comparisons was 0.72%, which is significantly below the accepted AHP threshold of 10%. This high level of internal consistency validates the logical soundness of the expert judgments, reinforcing the credibility of the prioritization results for use in infrastructure policy and planning.

3.3.3 With Respect to Social Sustainability

Table 4 below shows the normalized ranking of the sub-criteria with respect to environmental sustainability.

Table 4. Alternatives Rankings – Social Sustainability

	NORMALIZED					
CRITERIA	1	2	3	4	WEIGHTS	RANKING
1	1.00	1.15	1.45	1.47	**31.01%**	**1**
2	0.87	1.00	1.10	0.87	**23.64%**	**3**
3	0.69	0.91	1.00	0.79	**20.70%**	**4**
4	0.68	1.15	1.26	1.00	**24.66%**	**2**
Eigenvalue (γ_{max})					**4.014**	
Random Consistency Index (RI)					**0.90**	
Consistency Index (CI)					**0.01875**	
CONSISTENCY RATIO (CR)					**0.5162%**	

Within the domain of social sustainability, Cost Efficiency was prioritized most highly, with a weight of 31.01%. This result reflects the emphasis placed on ensuring that public infrastructure investments contribute to social returns such as job creation, local economic stimulation, and equitable growth. While often considered an economic concern, cost efficiency in this context may signal the importance of delivering value-for-money services that are socially inclusive and publicly accountable.

Closely following were Stakeholder Acceptance (24.66%) and Accessibility (23.64%), highlighting the multidimensional nature of social sustainability. These results reinforce the principle that socially sustainable seaport development must be participatory, equitable, and user-centered. Stakeholder inclusion in planning processes and equitable access to port-related benefits are increasingly recognized as essential to infrastructure legitimacy and long-term community support—consistent with findings in participatory planning literature [30].

Resilience ranked lowest at 20.70%, though it remains a relevant factor. This may reflect the perception that, from a purely social standpoint, climate adaptation and long-term infrastructure durability while important are less immediate to the lived experiences of port-adjacent communities than economic inclusion and governance.
The Consistency Ratio (CR) for the social sustainability sub-criteria was 0.52%, well below the 10% AHP threshold. This indicates that expert judgments were highly consistent and logically coherent, validating the robustness of the results for use in socially responsive infrastructure decision-making.

3.3.4 Overall Ranking of Sub-Criteria for Seaport Site Selection

Table 5.0. shows the aggregate ranking of sub-criteria for seaport site selection by multiplying the matrices to determine the global weights.

Table 5. Global Weights of sub-criteria factors

Critical Factors	Weight (%)	Rank
Cost Efficiency	33.45%	1
Stakeholder Acceptance	27.73%	2
Accessibility	21.24%	3
Resilience	17.58%	4

By aggregating the weighted results from the environmental, social, and economic dimensions of the Triple Bottom Line (TBL), Cost Efficiency emerged as the top-ranked sub-criterion, with an overall priority weight of 33.45%. This finding affirms that, even amid rising emphasis on sustainability, economic rationality continues to be the cornerstone of seaport planning. Effective site selection must therefore account for capital, operational, and maintenance expenditures to ensure long-term project viability and investor confidence. The result is consistent with long-established infrastructure planning literature, where cost-based evaluation remains central to feasibility assessment [34].

Stakeholder Acceptance was the second-highest sub-criterion, with a weight of 27.73%, highlighting the increasing importance of securing a social license to operate. Infrastructure projects that fail to consider public sentiment or stakeholder engagement risk facing delays, opposition, or outright cancellation. This underscores the shift toward participatory governance and community-inclusive planning, particularly for large-scale, high-impact developments like ports [30], [32].

Accessibility, weighted at 21.24%, ranked third overall. This result confirms that logistical connectivity remains a crucial determinant in seaport viability. Efficient links between maritime access points and inland markets are essential to achieving throughput targets and regional competitiveness. Poor accessibility can offset environmental and economic gains by limiting a port's ability to function as an effective trade hub.

Finally, Resilience received the lowest priority weight at 17.58%, though it still holds significance in sustainable planning. The relatively lower emphasis may reflect institutional limitations or the current developmental maturity of resilience planning in port infrastructure. Nonetheless, resilience to climate impacts and disruptions remains a critical long-term consideration, and its ranking should not be interpreted as a dismissal of its relevance, but rather as an indicator of current stakeholder focus during early project stages.

4. Conclusion

The findings derived from the Analytic Hierarchy Process (AHP) emphasize the need for a strategic and multidimensional approach to seaport development, one that reflects the complex interplay of economic viability, environmental stewardship, and social inclusion. Grounded in the Triple Bottom Line (TBL) framework and validated by expert judgment, this study offers a set of policy recommendations aimed at enhancing the sustainability and effectiveness of container seaport site selection in the Philippines.
The recommendations presented in Figure 3.0 are directly anchored on the ranked sub-criteria identified through AHP analysis: cost efficiency (33.45%), stakeholder acceptance (27.73%), accessibility (21.24%), and resilience (17.58%). Each recommendation reflects the empirical priorities identified by practitioners and stakeholders across sectors.
To present these findings in a structured and actionable form, the study introduces a Circular Policy Feedback Model for Sustainable Seaport Development (see Figure 3.0). This conceptual framework illustrates how the policy recommendations are organized into four

interdependent domains: economic sustainability, social sustainability, environmental sustainability, and integrated accessibility and logistics planning. Each domain addresses a specific set of priorities derived from the AHP results, and together they form a continuous policy cycle.

Fig. 3. Circular Policy Feedback Model for Sustainable Seaport Development

The circular layout emphasizes the cyclical and reinforcing nature of sustainable development, where improvements in one area influence and support progress in others. Moreover, the model incorporates a feedback mechanism to promote adaptive policy implementation, allowing for periodic evaluation and refinement based on changing conditions, stakeholder input, and performance monitoring.

4.1 Recommendations

While the study provides a robust framework for sustainable seaport site selection using the Triple Bottom Line (TBL) and Analytic Hierarchy Process (AHP), several areas remain open for future exploration. First, the model does not incorporate specific geographical, geotechnical, or spatial data, which could be addressed in future studies through the integration of GIS-based analysis for real-world site validation. Second, the model is static and does not account for long-term environmental, economic, or geopolitical changes; thus, researchers are encouraged to apply scenario-based modeling or system dynamics to capture temporal variability. Third, while expert judgment was used to establish priorities, no sensitivity or uncertainty analysis was conducted; future work may benefit from incorporating fuzzy AHP or sensitivity testing to assess the robustness of results under varied assumptions.

Moreover, the study's reliance on expert respondents limits the breadth of stakeholder representation. Future studies should involve a wider range of actors, including local communities, indigenous groups, and civil society, to enrich the participatory dimension of port planning. Institutional and regulatory factors were also outside the scope of this study yet play a critical role in project implementation; future frameworks may incorporate legal and governance criteria. Additionally, while cost efficiency was prioritized, no quantitative economic modeling was performed—future research may employ cost-benefit or input-output analysis to estimate broader socioeconomic impacts. Finally, combining AHP with other decision-support tools such as TOPSIS or ANP may enhance the decision-making process by capturing interdependencies among criteria. These directions can strengthen the model's applicability and responsiveness to real-world complexities in sustainable port development.

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