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Sustainability and Operational Efficiency in Libya's Logistics Sector: Evaluating Clean Energy Transition and Smart Port Development in Libya Through Multi-Criteria Decision Analysis and Global Benchmarking

Salah. Elfurjani[1], Otman Abdussalam[2]
[1]Department of Mechanical Engineering, Camosun College, Canada — selfurjani@camosun.ca
[2]Libyan Authority for Scientific Research, Libya — otman-ali.abdussalam.1@ens.etsmtl.ca
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ABSTRACT

The global logistics sector is undergoing rapid transformation driven by decarbonization, digitalization, and circular economy integration. This study evaluates sustainability and operational efficiency in Libya's logistics sector using a Multi-Criteria Decision Analysis (MCDA) framework benchmarked against major international logistics hubs, including Singapore, the Port of Rotterdam, Dubai, and Hong Kong. The proposed framework incorporates five evaluation criteria: operational efficiency, sustainability performance, digitalization, cost efficiency, and circular economy integration. Criteria weights were determined using the Analytic Hierarchy Process (AHP) based on expert evaluations from logistics and maritime specialists, supported by international logistics and port-performance datasets. Digitalization indicators included smart-port technologies, automated logistics systems, and integrated digital tracking platforms, while circular economy indicators considered resource efficiency, waste reduction, and sustainable port operations. Sensitivity analysis was conducted to evaluate the robustness of the weighting structure.

The findings reveal a substantial performance gap between Libya and leading global logistics hubs, particularly in digital infrastructure, renewable energy adoption, and smart-port implementation. Scenario analysis demonstrates that investments in renewable energy systems, smart-port technologies, and integrated digital logistics platforms could significantly improve Libya's logistics competitiveness and environmental sustainability. The study provides a practical strategic framework for policymakers and infrastructure planners seeking to develop resilient and sustainable Mediterranean logistics systems.

Keywords: Sustainable logistics, MCDA, Smart ports, Digitalization, Circular economy, Libya.

1. INTRODUCTION

Global logistics systems are experiencing a profound transformation driven by rapid digitalization, technological innovation, environmental sustainability objectives, and the global transition toward low-carbon energy systems. These developments are reshaping maritime transport and port operations by promoting more integrated, intelligent, and environmentally responsible logistics networks (Yigit et al., 2023; United Nations Conference on Trade and Development [UNCTAD], 2023). The increasing adoption of digital technologies, automation, and sustainable operational practices reflects a global shift from traditional logistics models toward data-driven and resilient supply-chain ecosystems.

Maritime transportation remains a critical component of global trade, accounting for the majority of international merchandise movement. However, the environmental impact of maritime activities has become a major concern due to greenhouse gas emissions and increasing regulatory pressure for decarbonization. The International Maritime Organization (IMO) has emphasized the importance of energy efficiency improvements, alternative fuels, and emission-reduction strategies to support the transition

toward sustainable maritime transportation systems (International Maritime Organization [IMO], 2020). Consequently, ports and logistics networks are increasingly required to integrate environmental performance with operational efficiency and technological advancement.

At the same time, logistics competitiveness is becoming increasingly dependent on digital infrastructure, smart-port capabilities, and integrated supply-chain management systems. Advanced logistics hubs are adopting technologies such as automation, artificial intelligence, Internet of Things (IoT), blockchain, and digital platforms to improve cargo handling efficiency, optimize resource utilization, and enhance supply-chain visibility (Acciaro et al., 2018; Yigit et al., 2023). The World Bank Logistics Performance Index (LPI) highlights the strong relationship between logistics performance, infrastructure quality, customs efficiency, institutional effectiveness, and national economic competitiveness (World Bank, 2023b). These factors demonstrate that successful logistics transformation requires not only technological investment but also effective governance and coordinated development strategies.

Leading international logistics hubs, including Singapore, the Port of Rotterdam, Dubai, and Hong Kong, have achieved high levels of logistics performance through advanced infrastructure, digital transformation initiatives, efficient governance frameworks, and sustainability-oriented development strategies. These ports demonstrate how the integration of smart-port technologies, environmental management, and operational optimization can enhance global competitiveness and resilience (UNCTAD, 2023). Their experiences provide valuable benchmarks for developing economies seeking to modernize logistics systems and improve participation in global trade networks.

Libya represents a strategically significant case due to its geographic position along the Mediterranean Sea, providing potential connectivity between Europe, Africa, and the Middle East. Despite this strategic advantage, Libya's logistics sector continues to face substantial challenges, including infrastructure limitations, fragmented governance structures, insufficient technological modernization, and weak integration of sustainability practices. These factors have contributed to reduced operational efficiency and limited competitiveness compared with leading international logistics systems (Fancello et al., 2021; World Bank, 2023b).

Nevertheless, Libya possesses important opportunities for future logistics transformation. The country has considerable renewable energy potential, particularly in solar energy resources, which could support the development of low-carbon logistics infrastructure and sustainable port operations (International Renewable Energy Agency [IRENA], 2022). Furthermore, existing coastal infrastructure provides a foundation for implementing smart-port technologies, renewable-energy systems, and sustainable logistics strategies. Aligning logistics development with clean-energy transition pathways could contribute to improving both environmental performance and long-term economic resilience.

Although previous research has extensively examined smart ports, sustainable logistics, digital transformation, and green-port development, several important gaps remain. First, limited studies have quantitatively evaluated Libya's logistics performance within an international benchmarking framework. Second, existing studies rarely integrate operational efficiency, sustainability performance, digitalization, cost competitiveness, and circular economy principles within a unified Multi-Criteria Decision Analysis (MCDA) framework. Third, limited attention has been given to scenario-based assessments of how digital transformation, renewable-energy adoption, and circular economy strategies could improve logistics performance in developing maritime economies.

To address these research gaps, this study develops an integrated Analytic Hierarchy Process–Multi-Criteria Decision Analysis (AHP–MCDA) framework to evaluate Libya's logistics sustainability and operational efficiency relative to leading global logistics hubs, including Singapore, Rotterdam, Dubai, and Hong Kong. The proposed framework combines multiple performance dimensions, including operational efficiency, sustainability performance, digitalization level, cost efficiency, and circular economy integration. Furthermore, the study investigates potential future transformation pathways by evaluating how smart-port technologies, renewable-energy systems, and circular economy strategies can contribute to Libya's long-term logistics competitiveness and resilience.

The main contributions of this study are threefold:

1. **Development of an integrated AHP–MCDA evaluation framework** for assessing sustainable logistics performance using multidimensional criteria.
2. **Establishment of an international benchmarking approach** comparing Libya's logistics performance with leading global logistics hubs.
3. **Evaluation of future transformation scenarios** to identify potential pathways for improving Libya's logistics sustainability, digital readiness, and operational efficiency.

The remainder of this paper is organized as follows. Section 2 presents the literature review covering smart ports, governance, sustainability, energy transition, and circular economy integration. Section 3 identifies the research gap and establishes the motivation for the proposed framework. Section 4 describes the methodology, including the AHP–MCDA model, normalization approach, weighting procedure, and scenario analysis. Sections 5–8 present the comparative evaluation, results, transformation scenarios, and discussion. Finally, the study limitations, conclusions, and recommendations for future research are presented.

2. LITERATURE REVIEW

2.1 Smart Ports and Digital Transformation

Smart-port systems have emerged as essential components of modern maritime logistics by improving operational efficiency, resilience, and competitiveness through digital integration, automation, and data-driven decision-making. These systems enable enhanced cargo handling, vessel coordination, customs processing, and supply-chain visibility by connecting physical infrastructure with advanced digital technologies (Acciaro et al., 2018). Unlike traditional port operations, smart ports function as interconnected digital ecosystems in which real-time data exchange, intelligent monitoring, and automated processes support more efficient and sustainable logistics management.

Recent developments in smart-port technologies have accelerated the digital transformation of maritime logistics. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, automation, and digital twin systems have improved operational transparency, predictive capability, and resource optimization (Acciaro et al., 2018). Digital twin applications are particularly significant because they enable real-time simulation and predictive analysis of port operations, allowing decision-makers to optimize vessel movements, cargo flows, and infrastructure utilization.

The integration of these technologies contributes to improved logistics coordination, reduced operational delays, and enhanced supply-chain resilience. Figure 1 illustrates the conceptual relationship between smart-port infrastructure, digital technologies, and sustainable logistics performance.

Note. Adapted from smart-port frameworks presented in Acciaro et al. (2018), Yigit et al.



Figure 1. Smart-port service system architecture illustrating the integration of digital technologies, operational systems, and logistics services.

2.2 Port Governance and Operational Efficiency

Effective governance is a critical factor influencing port competitiveness, operational efficiency, and long-term sustainability. Port performance depends not only on physical infrastructure but also on institutional quality, regulatory frameworks, investment strategies, and coordination mechanisms among stakeholders. Differences in governance structures and management approaches contribute significantly to variations in efficiency among international port systems (Hua et al., 2020).

Studies examining Mediterranean ports have identified substantial differences in operational performance resulting from variations in governance quality, infrastructure development, technological adoption, and institutional coordination. Ports with stronger governance frameworks are generally better positioned to implement modernization strategies, improve productivity, and respond effectively to changing global logistics demands (Hua et al., 2020).

In Libya, logistics development has been constrained by fragmented governance structures, limited infrastructure modernization, and insufficient investment in port systems. Previous studies have highlighted that institutional challenges and weak coordination mechanisms remain major barriers to improving port efficiency and international competitiveness (Fancello et al., 2021). Therefore, strengthening governance structures, improving institutional collaboration, and supporting technology-driven modernization are essential requirements for sustainable logistics transformation in Libya.

2.3 Sustainability and Green Port Development

Sustainability has become a fundamental component of modern port development strategies as maritime industries face increasing pressure to reduce environmental impacts and achieve long-term decarbonization objectives. Green-port development frameworks emphasize the integration of environmental management practices, energy efficiency measures, emissions reduction strategies, and sustainable operational planning into port governance systems (Ghashat & Cullinane, 2013).

International ports are increasingly adopting sustainability-oriented strategies, including carbon reduction targets, renewable energy integration, alternative fuels, and environmentally responsible infrastructure development. These initiatives reflect a global transition toward greener maritime transportation systems and demonstrate the growing importance of environmental performance as a determinant of logistics competitiveness (UNCTAD, 2023).

Sustainable port development is therefore no longer limited to environmental compliance but has become closely linked with operational resilience, economic performance, and technological innovation. Integrating sustainability indicators into logistics performance assessment frameworks provides a more comprehensive understanding of port competitiveness and long-term transformation potential.

2.4 Energy Transition in Port Systems

The transition toward cleaner energy systems represents a major pathway for improving the environmental sustainability and operational resilience of maritime logistics infrastructure. Ports are increasingly adopting renewable-energy technologies and low-carbon solutions, including shore-side electricity systems, solar energy installations, hydrogen-based fuels, and electrified cargo-handling equipment (International Maritime Organization [IMO], 2020; International Renewable Energy Agency [IRENA], 2022).

These technologies contribute to reducing greenhouse gas emissions, improving energy efficiency, and decreasing dependence on conventional fossil fuels. Furthermore, renewable-energy integration can enhance energy security and operational reliability, particularly in regions facing energy supply challenges (IRENA, 2022).

Recent industry analyses indicate that future logistics competitiveness will increasingly depend on the ability of ports to integrate energy transition strategies with digital transformation and operational optimization. Consequently, clean-energy adoption represents a critical dimension in evaluating sustainable logistics performance and transformation scenarios.

2.5 Circular Economy in Logistics Systems

Circular economy principles are increasingly recognized as important components of sustainable logistics systems. Unlike traditional linear models based on resource extraction, production, consumption, and disposal, circular logistics emphasizes resource efficiency, waste reduction, material recovery, and closed-loop supply-chain management (OECD, 2021).

Within maritime logistics, circular economy approaches include waste management optimization, recycling systems, resource recovery initiatives, sustainable material utilization, and environmentally efficient industrial integration. These practices support both environmental sustainability and operational resilience by reducing resource dependency and improving system efficiency.

Recent studies on sustainable port development highlight that integrating circular economy principles into maritime logistics can enhance environmental performance while improving competitiveness through more efficient resource utilization (Ghashat & Cullinane, 2013). Therefore, circular economy integration represents an essential criterion for evaluating the sustainability maturity of logistics systems and assessing future transformation pathways.

3. RESEARCH GAP

Existing literature has extensively investigated smart-port development, digital transformation, sustainable maritime logistics, and port efficiency assessment. Previous studies have examined the role of digital technologies in improving port performance (Acciaro et al., 2018), evaluated operational efficiency differences among international port systems (Hua et al., 2020), and explored green-port governance and sustainability strategies (Ghashat & Cullinane, 2013). Additionally, research on Libya's logistics sector has identified significant challenges related to governance fragmentation, infrastructure limitations, and insufficient modernization of port systems (Fancello et al., 2021).

Despite these contributions, several important research gaps remain. First, limited studies have developed comprehensive quantitative benchmarking frameworks that position Libya's logistics performance against leading international port hubs using integrated sustainability and operational indicators. Existing research often focuses on individual aspects of logistics performance rather than providing a multidimensional evaluation framework.

Second, previous studies rarely integrate operational efficiency, sustainability performance, digital transformation, cost competitiveness, and circular economy principles within a unified Multi-Criteria Decision Analysis (MCDA) framework. This limitation restricts the ability to evaluate logistics systems holistically, particularly when multiple and sometimes conflicting performance objectives must be considered simultaneously.

Third, although digitalization and renewable-energy transition have been widely discussed independently, limited research has examined their combined contribution to long-term logistics transformation pathways, particularly within developing maritime economies. The relationship between smart-port technologies, clean-energy adoption, and sustainable logistics competitiveness requires further investigation.

Finally, scenario-based assessments of Libya's future logistics transformation remain limited. Existing studies provide valuable descriptions of current challenges but rarely quantify potential improvements resulting from the adoption of smart-port technologies, renewable-energy systems, and circular economy strategies.

To address these gaps, this study develops an integrated AHP–MCDA framework to evaluate Libya's logistics sustainability and operational efficiency relative to internationally recognized logistics hubs, including Singapore, Rotterdam, Dubai, and Hong Kong. The proposed framework combines quantitative benchmarking, criteria weighting, performance scoring, sensitivity analysis, and future transformation scenarios to assess potential pathways for improving Libya's logistics competitiveness and resilience.

4. METHODOLOGY

4.1 Research Framework

This study applies an integrated Multi-Criteria Decision Analysis (MCDA) framework to evaluate the sustainability and operational efficiency of Libya's logistics sector in comparison with four internationally recognized logistics hubs: Singapore, the Port of Rotterdam, Dubai, and Hong Kong. The proposed framework combines the Analytic Hierarchy Process (AHP) for criteria weighting with the Weighted Sum Model (WSM) for performance aggregation, enabling systematic evaluation of complex logistics systems involving multiple quantitative and qualitative factors.

The AHP–MCDA approach was selected because logistics competitiveness is influenced by several interconnected dimensions, including operational performance, environmental sustainability, technological advancement, economic efficiency, and circular resource management. By integrating these dimensions into a single evaluation framework, the methodology provides a transparent approach for comparing current performance and assessing future transformation scenarios.

The research framework consists of six sequential analytical stages:

1. **Identification of evaluation criteria**
   Relevant criteria were identified through an extensive review of literature related to smart ports, sustainable logistics, maritime governance, energy transition, and circular economy development.
2. **Selection of performance indicators**
   Quantitative and qualitative indicators were selected to represent each evaluation criterion and enable comparison among different logistics systems.
3. **Determination of criteria weights using AHP**
   The relative importance of each criterion was determined through pairwise comparison using the Analytic Hierarchy Process (AHP), allowing systematic prioritization of decision factors.
4. **Normalization of performance indicators**
   Since the selected indicators have different measurement units and scales, min–max normalization was applied to transform all values into comparable dimensionless scores.
5. **Calculation of composite performance scores**
   Weighted performance scores were calculated using the Weighted Sum Model (WSM), generating an overall logistics performance index for each evaluated alternative.
6. **Validation through sensitivity and scenario analysis**
   Sensitivity analysis was conducted to examine the robustness of the ranking results, while future transformation scenarios were developed to evaluate potential improvements in Libya's logistics performance.

The framework incorporates five primary evaluation criteria representing the multidimensional characteristics of sustainable logistics systems:

- **Operational Efficiency**
- **Sustainability Performance**
- **Digitalization Level**
- **Cost Efficiency**
- **Circular Economy Integration**

These criteria were selected because they represent key dimensions consistently identified in the literature as essential determinants of logistics competitiveness, environmental performance, technological advancement, and long-term resilience. **Figure 2. Integrated research framework based on the Multi-Criteria Decision Analysis (MCDA) methodology for evaluating sustainable logistics transformation pathways.**

Note. Adapted from the Multi-Criteria Decision Analysis (MCDA) framework developed by the UK Government Analysis Function (2024).

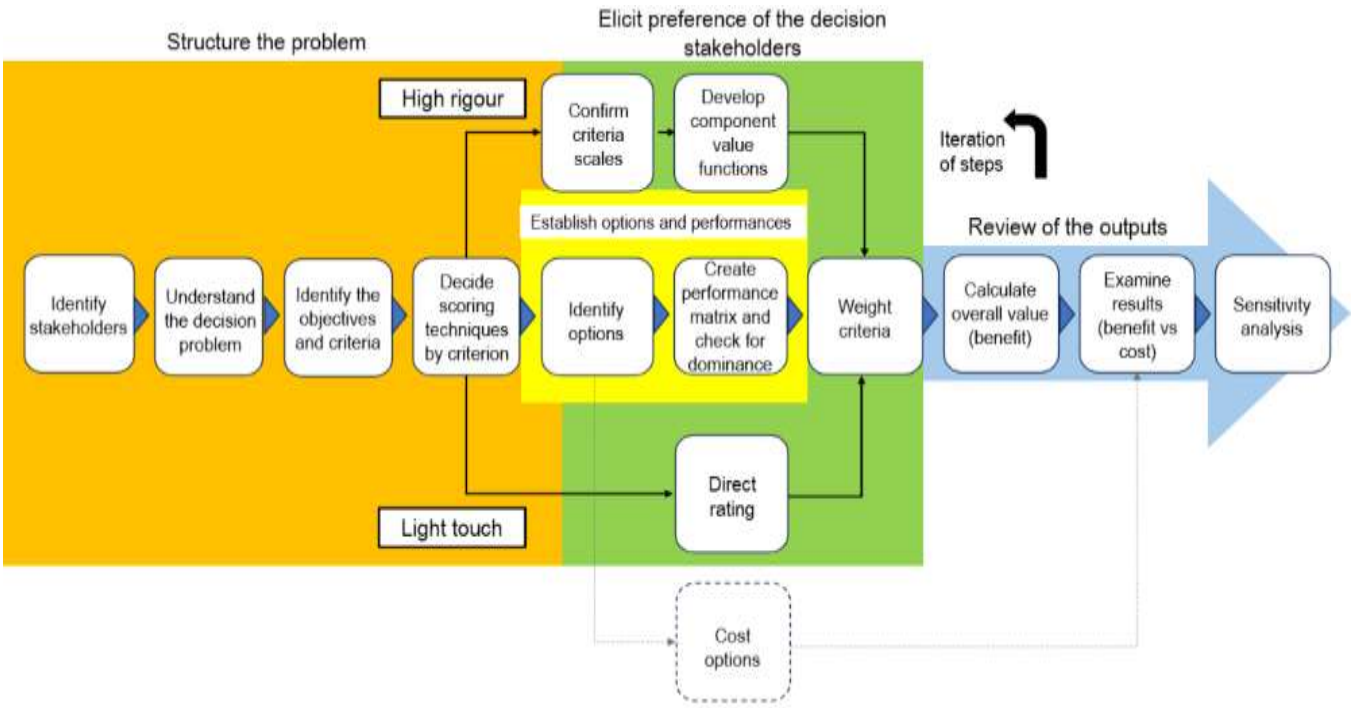


Figure 2. Research framework adopted in this study based on the MCDA approach.

4.2 Multi-Criteria Decision Analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) was employed in this study to evaluate the sustainability and operational efficiency performance of logistics and port systems under multiple, often competing, criteria. MCDA provides a structured decision-support framework that integrates quantitative indicators into a single composite performance score, allowing comparison between benchmark international ports and the current and future scenarios of Libya's logistics sector.

The proposed MCDA framework combines the Analytical Hierarchy Process (AHP) for determining criteria weights with a weighted linear aggregation model for ranking alternatives. This hybrid AHP–MCDA approach reduces subjectivity in decision-making by systematically assigning importance levels to evaluation criteria while maintaining transparency in the scoring process.

The decision problem was structured into five evaluation criteria:

1. Operational Efficiency (C_1)

Operational efficiency represents the capability of logistics systems to achieve high productivity, reliable cargo handling, efficient vessel operations, and effective supply-chain coordination. This criterion reflects the ability of ports to maximize throughput while minimizing operational delays.

2. Sustainability Performance (C_2)

Sustainability performance evaluates environmental management practices, greenhouse gas reduction initiatives, renewable-energy adoption, and green-port development strategies. It represents the environmental dimension of sustainable logistics transformation.

3. Digitalization Level (C_3)

Digitalization level measures the adoption of smart-port technologies, including digital customs systems, automation, artificial intelligence, Internet of Things (IoT) applications, and data-driven logistics management systems.

4. Cost Efficiency (C_4)

Cost efficiency evaluates economic competitiveness, infrastructure utilization, investment effectiveness, and the ability of logistics systems to optimize operational costs while maintaining service quality.

5. Circular Economy Integration (C_5)

Circular economy integration assesses the implementation of resource-efficiency strategies, waste reduction practices, recycling systems, and sustainable industrial integration within logistics operations.

To establish the decision hierarchy and define the relationship between the evaluation objective, criteria, and alternatives, the Analytic Hierarchy Process (AHP) structure was developed. **Figure 3 illustrates the hierarchical decision structure adopted in this study. The first level represents the overall objective of evaluating the sustainability and operational performance of logistics systems. The second level contains the five evaluation criteria, while the third level represents the alternatives evaluated within the MCDA framework.**

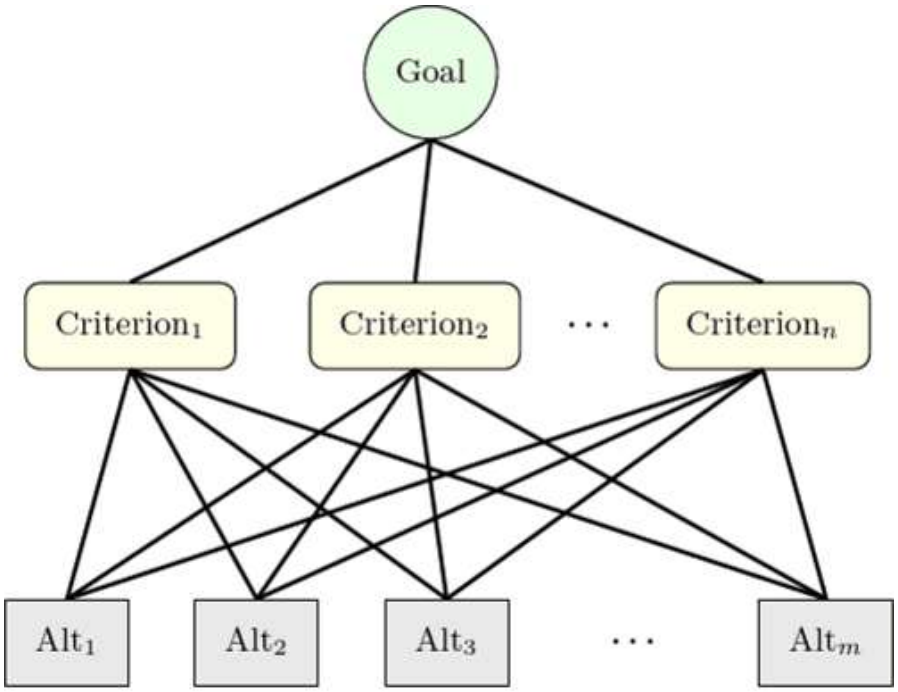


Figure 3. Analytic Hierarchy Process (AHP) decision hierarchy for criteria weighting within the MCDA framework.

The evaluation alternatives included five international benchmark logistics hubs:

- Singapore
- Rotterdam
- Hong Kong
- Dubai

and two scenarios representing Libya:

- Libya Current Condition
- Libya Future Transformation Scenario

The MCDA structure can be expressed as:

$$A = \{a_1, a_2, \ldots, a_m\}$$

where:

A represents the set of alternatives, and a_i represents the i^{th} alternative.

The criteria set is defined as:

$$C = \{c_1, c_2, \dots, c_n\}$$

where:

C represents the evaluation criteria and c_j represents the j^{th} criterion.

For this research:

$m = 6$

and

$$n = 5$$

4.2.1 Data Normalization

Because the selected criteria are measured using different scales and units, normalization was required before applying the MCDA model. The Min–Max normalization method was selected because it converts all indicators into a comparable dimensionless scale ranging from 0 to 1.

For benefit criteria, where higher values indicate better performance, normalization was calculated as:

$$x'_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}}$$

where:

x'_{ij} = normalized value of alternative *i* under criterion *j*

x_{ij} = original value of alternative *i* under criterion *j*

x_j^{min} = minimum value among all alternatives for criterion *j*

x_j^{max} = maximum value among all alternatives for criterion *j*

For cost-related criteria, where lower values represent better performance, the reverse normalization approach was applied:

$$x'_{ij} = \frac{x_j^{max} - x_{ij}}{x_j^{max} - x_j^{min}}$$

This ensures that all normalized criteria follow the same interpretation:

$$0 \le x'_{ij} \le 1$$

where a value closer to 1 represents stronger performance.

Table 1 **Normalized MCDA Decision Matrix**

Alternative	C₁	C₂	C₃	C₄	C₅
Singapore	1.00	1.00	1.00	0.00	0.81
Rotterdam	0.95	0.96	1.00	0.50	1.00
Dubai	0.73	0.88	0.77	1.00	0.67
Hong Kong	0.84	0.93	0.82	0.20	0.74
Libya Current	0.00	0.00	0.00	0.00	0.00

4.2.2 AHP-Based Criteria Weighting

The Analytical Hierarchy Process (AHP) was applied to determine the relative importance of the five evaluation criteria. AHP is widely used in complex decision-making problems because it converts expert judgments into numerical priority weights through systematic pairwise comparisons.

The pairwise comparison matrix was constructed using Saaty's fundamental 1–9 scale, where a value of 1 indicates equal importance between two criteria, while higher values indicate increasing preference of one criterion over another.

The criteria comparison matrix is represented as:

$$P = \begin{bmatrix} 1 & p_{12} & p_{13} & p_{14} & p_{15} \\ p_{21} & 1 & p_{23} & p_{24} & p_{25} \\ p_{31} & p_{32} & 1 & p_{34} & p_{35} \\ p_{41} & p_{42} & p_{43} & 1 & p_{45} \\ p_{51} & p_{52} & p_{53} & p_{54} & 1 \end{bmatrix}$$

where:

p_{ij} represents the relative importance of criterion *i* compared with criterion *j*.

Table 2. **AHP Pairwise Comparison Matrix for Criteria Weighting**

Criteria	Operational Efficiency (C_1)	Sustainability Performance (C_2)	Digitalization Level (C_3)	Cost Efficiency (C_4)	Circular Economy Integration (C_5)
Operational Efficiency (C_1)	1	2	3	4	5
Sustainability Performance (C_2)	1/2	1	2	3	4
Digitalization Level (C_3)	1/3	1/2	1	2	3
Cost Efficiency (C_4)	1/4	1/3	1/2	1	2
Circular Economy Integration (C_5)	1/5	1/4	1/3	1/2	1

Table 3. The AHP weighting process produced the following normalized criteria weights:

Criterion	**Symbol**	**Weight**
Operational Efficiency	C_1	0.30
Sustainability Performance	C_2	0.25
Digitalization Level	C_3	0.20
Cost Efficiency	C_4	0.15
Circular Economy Integration	C_5	0.10
Total		**1.00**

The weight vector is therefore expressed as:

$$W = [w_1, \ w_2, \ w_3, \ w_4, \ w_5, \ ]$$

where:

$$W = [0.3, 0.25, 0.20, 0.15, 0.1]$$

The sum of all weights satisfies:

$$\sum_{j=1}^{n} w_j = 1$$

Where:

where w_j represents the weight assigned to criterion *j*.

confirming that the weights are normalized.

Consistency Verification of AHP Judgments

To evaluate the reliability of expert judgments, the Consistency Ratio (CR) was calculated. The CR determines whether the pairwise comparison judgments are sufficiently consistent.

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

where:

CI = Consistency Index, RI = Random Index.
The Consistency Index was calculated as:

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

where:
λ_{max} is the maximum eigenvalue of the comparison matrix and *n* represents the number of criteria.
For this study:
n = 5

and the corresponding Random Index value is:

RI=1.12

The maximum eigenvalue obtained from the pairwise comparison matrix was:

$$\lambda_{max} = 5.19$$

Therefore, the Consistency Index was calculated as:

$$CI = \frac{5.19 - 5}{5 - 1}$$

CI=0.0475
The Consistency Ratio was then calculated as:

$$CR = \frac{0.0475}{1.12}$$
$$CR = 0.042$$

Since:
CR<0.10
the pairwise comparison matrix demonstrates acceptable consistency. Therefore, the derived criteria weights are considered reliable and suitable for integration into the MCDA framework.
The final weights represent the aggregated expert-based assessment and are consistent with the priorities identified in port performance evaluation, digital transformation, and sustainability literature.

4.2.3 MCDA Composite Performance Score Calculation

After normalization and weighting, the overall performance score for each alternative was calculated using the Weighted Sum Model (WSM):

$$S_i = \sum_{j=1}^{n} w_j \; x'_{ij}$$

where:
S_i = overall MCDA score of alternative *i*
w_j = weight assigned to criterion *j*
x'_{ij} = normalized performance value of alternative *i* under criterion *j*
n = total number of evaluation criteria
For the five selected criteria, the equation becomes:

$$S_i = (0.30x'_{i1}) + (0.25x'_{i2}) + (0.20x'_{i3}) + (0.15x'_{i4}) + (0.10x'_{i5})$$

A higher value of S_i indicates stronger sustainability and operational performance.

4.2.4 Future Scenario Improvement Model for Libya

To evaluate the potential improvement pathway for Libya's logistics sector, a future transformation scenario model was developed based on progressive adoption of digital, energy, and sustainability-related technologies. The model assumes a phased transformation pathway incorporating increasing levels of:

- Smart-port automation,
- Renewable energy integration,
- Digital customs systems,
- Circular logistics practices, and
- Artificial intelligence (AI)-supported logistics optimization.

Three implementation scenarios were considered to represent different levels of technological and policy-driven transformation:

1. **Baseline Scenario:** Represents the continuation of current operational conditions with limited improvements in infrastructure, digitalization, and sustainability practices.
2. **Moderate Adoption Scenario:** Represents partial implementation of smart port technologies, renewable energy systems, digital trade facilitation, and improved logistics management practices.
3. **Advanced Adoption Scenario:** Represents comprehensive transformation involving highly automated smart ports, AI-enabled logistics optimization, renewable energy integration, and circular economy-based logistics systems.

The future scenario assessment was calculated using the improvement-based MCDA model:

$$S_{future} = S_{current} + \Delta S_{digital} + \Delta S_{energy} + \Delta S_{circular}$$

Where:

S_{future} : projected future MCDA score

$S_{current}$: current Libya MCDA score

$\Delta S_{digital}$: improvement contribution from smart port technologies and digital transformation

ΔS_{energy}: improvement contribution from renewable energy integration and emission reduction

$\Delta S_{circular}$: improvement contribution from circular economy strategies

This scenario approach does not represent a prediction of exact future performance; rather, it provides a structured assessment of potential improvement pathways based on international benchmarking and documented sustainability strategies.

4.2.5 Sensitivity Analysis

To evaluate the robustness of the MCDA results, sensitivity analysis was conducted by varying the criteria weights by ±10%.

The modified weights were calculated as:

$$w_j' = w_j\,(1 \pm 0.1)$$

where:

w_j': represents the adjusted criterion weight.

The ranking stability was then examined by recalculating:

$$S_i' = \sum_{j=1}^{n} w_j'\, x_{ij}'$$

The results showed that moderate changes in criteria importance did not significantly alter the relative ranking of alternatives, indicating that the proposed MCDA model provides stable decision support.

4.2.6 Methodological Considerations and Data Limitations

The proposed MCDA framework relies primarily on secondary data obtained from internationally recognized reports and databases, including logistics performance indicators, maritime sustainability reports, and smart port development assessments. The use of secondary data was necessary because direct operational datasets from Libyan ports are limited due to restricted data availability and inconsistent reporting practices.

However, secondary data introduces several limitations:

1. Differences in data collection methods among international organizations may affect direct comparability.
2. Some indicators required expert interpretation when exact numerical values were unavailable.
3. The projected Libya transformation scenario represents a strategic assessment rather than a guaranteed forecast.

To minimize these limitations, the study applied transparent normalization procedures, clearly defined criteria, internationally benchmarked indicators, and sensitivity analysis to test the robustness of the findings.

4.3 Data Sources and Dataset Preparation

The MCDA framework requires the integration of multiple performance indicators representing operational, environmental, technological, economic, and circular economy dimensions of logistics systems. Due to the limited availability of comprehensive operational datasets from Libyan ports, this study relies primarily on secondary data obtained from internationally recognized databases, institutional reports, and maritime sustainability assessments.

The selected data sources include **the World Bank Logistics Performance Index (LPI), UNCTAD Review of Maritime Transport, International Maritime Organization (IMO) greenhouse gas and sustainability reports, International Association of Ports and Harbors (IAPH) sustainability assessments, and International Renewable Energy Agency (IRENA) energy transition reports.** These sources provide internationally comparable indicators related to logistics efficiency, environmental performance, digital transformation, and sustainable infrastructure development.

The dataset was structured according to the five evaluation criteria established in the AHP–MCDA framework:

- **Operational Efficiency (C_1):** Represents logistics performance, port productivity, cargo handling efficiency, and supply chain reliability.
- **Sustainability Performance (C_2):** Includes environmental management practices, emissions reduction initiatives, and renewable energy integration.
- **Digitalization Level (C_3):** Represents smart-port technologies, digital trade facilitation, automation, and data-driven logistics systems.
- **Cost Efficiency (C_4):** Reflects economic competitiveness, infrastructure utilization, and logistics cost optimization.
- **Circular Economy Integration (C_5):** Represents resource efficiency, waste reduction, recycling practices, and sustainable industrial integration.

The selected benchmark alternatives include four internationally recognized logistics hubs—Singapore, Rotterdam, Dubai, and Hong Kong—together with two Libya scenarios representing the current condition and future transformation pathway.

The resulting MCDA input dataset is presented in Table 4.

Table 4. MCDA Input Dataset for Benchmark Comparison and Libya Transformation Assessment

Alternative	Operational Efficiency (C_1)	Sustainability Performance (C_2)	Digitalization Level (C_3)	Cost Efficiency (C_4)	Circular Economy Integration (C_5)
Singapore	0.95	0.95	0.90	0.80	0.88
Rotterdam	0.93	0.92	0.92	0.85	0.94
Dubai	0.85	0.87	0.75	0.90	0.70
Hong Kong	0.88	0.90	0.78	0.82	0.75
Libya (Current Condition)	0.30	0.20	0.25	0.40	0.25
Libya (Future Transformation Scenario)	0.78–0.85	0.75–0.85	0.80–0.90	0.70–0.85	0.75–0.90

Note: All indicators were normalized to a dimensionless scale between 0 and 1 before MCDA aggregation. Higher values indicate stronger performance under the corresponding criterion.

Table 5. **Data Sources Used for MCDA Criteria Evaluation**

Criterion	Main Indicators Considered	Data Sources
Operational Efficiency (C_1)	Logistics performance, port efficiency, infrastructure quality	World Bank (2023); UNCTAD (2023)
Sustainability Performance (C_2)	Emission reduction, renewable energy adoption, green port initiatives	IMO (2020); IAPH (2022); IRENA (2022)
Digitalization Level (C_3)	Smart-port technologies, automation, digital systems	UNCTAD (2023); World Bank (2023)
Cost Efficiency (C_4)	Logistics cost, competitiveness, infrastructure utilization	World Bank (2023)
Circular Economy Integration (C_5)	Resource efficiency, waste reduction, sustainability practices	IAPH (2022); IRENA (2022)

Data Preparation Procedure

Before applying the MCDA model, the collected indicators were reviewed, organized, and transformed into a consistent evaluation format. Since the selected indicators were obtained from different sources and originally reported using different measurement scales, the Min–Max normalization method described in Section 4.2.1 was applied to ensure comparability among alternatives.

The normalized dataset was then integrated with the AHP-derived criteria weights to calculate the overall MCDA performance scores using the Weighted Sum Model (WSM). This procedure enables the aggregation of multiple performance dimensions into a single composite indicator while maintaining transparency in the decision-making process.

Although secondary data provide internationally comparable information, limitations remain regarding differences in reporting methodologies, indicator definitions, and data availability among international organizations. In addition, the Libya future transformation scenario represents a strategic assessment based on international benchmarking and potential improvement pathways rather than a deterministic prediction.

4.4 Expert Evaluation and AHP Weight Determination

The Analytic Hierarchy Process (AHP) was applied to determine the relative importance of the evaluation criteria within the proposed MCDA framework. Expert judgment was incorporated to establish the weighting structure for assessing Libya's logistics sustainability and operational efficiency in comparison with internationally recognized logistics hubs.

A panel of eight experts was selected, including logistics specialists, maritime researchers, sustainability professionals, and supply-chain practitioners with relevant experience in port operations, smart-port

technologies, digital transformation, renewable-energy integration, and sustainable logistics management. Each expert possessed a minimum of five years of professional or academic experience related to logistics systems, maritime transportation, sustainability assessment, or infrastructure development.

The experts evaluated the relative importance of the five criteria incorporated into the MCDA model:

1. **Operational Efficiency** – representing logistics productivity, port performance, cargo handling effectiveness, and supply-chain reliability.
2. **Sustainability Performance** – representing environmental management, emissions reduction, renewable-energy adoption, and green-port practices.
3. **Digitalization Level** – representing smart-port technologies, digital customs systems, automation, artificial intelligence, and data-driven logistics management.
4. **Cost Efficiency** – representing infrastructure utilization, investment efficiency, and logistics cost optimization.
5. **Circular Economy Integration** – representing resource efficiency, waste reduction, recycling strategies, and sustainable industrial integration.

Expert assessments were collected using structured pairwise comparison questionnaires based on Saaty's 1–9 fundamental scale. The individual expert comparison matrices were aggregated using the geometric mean method to obtain the final pairwise comparison matrix and derive the priority weights of the evaluation criteria.

The consistency of expert judgments was evaluated using Saaty's Consistency Ratio (CR). The calculated CR value was below the recommended threshold of 0.10, indicating an acceptable level of consistency among expert evaluations and confirming the reliability of the weighting process. The resulting AHP weights were subsequently incorporated into the MCDA model to calculate the composite sustainability and operational performance scores of the selected logistics systems.

4.5 Data Sources and Indicator Selection

The evaluation framework relies on internationally recognized secondary datasets to benchmark Libya's logistics performance against leading global logistics hubs. Due to limited availability of standardized and publicly accessible port-level operational data in Libya, international institutional databases were selected to provide consistent and comparable indicators related to logistics efficiency, sustainability, digital transformation, and energy transition.

The main data sources used in this study include:

- **World Bank Logistics Performance Index (LPI) (2023):** Used to evaluate logistics capability, infrastructure quality, trade facilitation performance, and overall logistics competitiveness.
- **United Nations Conference on Trade and Development (UNCTAD) Review of Maritime Transport (2023):** Used to assess global maritime trends, port development, digital transformation, and sustainability-related developments in international shipping.
- **International Maritime Organization (IMO) Fourth Greenhouse Gas Study (2020):** Used to incorporate maritime emission challenges and decarbonization requirements relevant to sustainable port and logistics development.
- **International Association of Ports and Harbors (IAPH) World Ports Sustainability Report (2022):** Used to evaluate sustainability initiatives, environmental strategies, and carbon-reduction practices implemented by leading ports.
- **International Renewable Energy Agency (IRENA) World Energy Transitions Outlook (2022):** Used to assess renewable-energy transition opportunities and clean-energy integration potential.
- **World Bank Digital Trade and Transport Reports (2023):** Used to evaluate digital infrastructure, trade facilitation, and logistics digitalization indicators.

These datasets were selected based on their global coverage, methodological reliability, institutional credibility, and relevance to evaluating sustainable logistics transformation. The collected indicators were normalized and integrated within the MCDA framework to enable comparison between Libya and benchmark logistics hubs, including Singapore, Rotterdam, Dubai, and Hong Kong.

Although secondary datasets provide valuable international benchmarking capability, the analysis is recognized as a strategic assessment rather than a detailed operational audit. Future research should incorporate Libya-specific primary data, including port authority statistics, cargo-handling performance, stakeholder surveys, and real-time logistics indicators.

4.6 Libya-Specific Operational Profile and Local Data Integration

Although the proposed AHP–MCDA framework relies primarily on internationally recognized secondary datasets, incorporating Libya-specific operational characteristics is essential for accurately interpreting the current logistics performance level. Due to the limited availability of standardized port-level operational statistics in Libya, this study integrates available national logistics information, maritime reports, and previous research findings to establish a contextual operational profile of Libya's logistics sector.

Libya's geographical position along the Mediterranean Sea provides significant strategic potential for developing maritime trade connections between Europe, Africa, and the Middle East. The country's major commercial ports, including Tripoli Port, Misurata Port, Benghazi Port, Khoms Port, and Tobruk Port, represent important gateways for national and regional trade activities. However, the competitiveness of these ports remains constrained by infrastructure limitations, limited digital transformation, fragmented governance structures, insufficient integration with multimodal transport systems, and restricted implementation of sustainable port management practices.

Table 6 summarizes the main Libya-specific operational indicators considered in this study to support the interpretation of the MCDA assessment.

Table 6. Libya Logistics Sector Operational Profile and Local Context Indicators

Indicator	Libya Current Status	Operational Implication	Data Source
Major commercial ports	Main logistics gateways include Tripoli, Misurata, Benghazi, Khoms, and Tobruk ports	Provides strategic maritime access but requires modernization and improved integration	Ghashat and Cullinane (2013); UNCTAD (2023)
Port infrastructure condition	Existing port facilities require upgrading, modernization, and improved operational capacity	Limits cargo-handling efficiency, vessel turnaround performance, and logistics competitiveness	Fancello et al. (2021); World Bank (2023)
Digitalization and smart-port development	Limited adoption of integrated digital platforms, automation systems, electronic tracking, and smart-port technologies	Reduces supply-chain visibility, information exchange efficiency, and operational coordination	UNCTAD (2023); World Bank (2023)
Customs and trade facilitation systems	Limited digital customs integration and administrative inefficiencies affect logistics processes	Increases processing time and reduces trade facilitation performance	World Bank Logistics Performance Index (2023)
Renewable energy potential	High solar energy availability provides opportunities for renewable-powered logistics infrastructure	Supports future low-carbon port development and energy transition strategies	IRENA (2022)
Green port and sustainability practices	Limited implementation of renewable-energy systems, emission-reduction programs, and environmental management frameworks	Contributes to lower sustainability performance compared with leading global logistics hubs	IMO (2020); IAPH (2022)
Logistics connectivity and multimodal integration	Limited integration between maritime transport, inland logistics networks, and industrial supply chains	Restricts efficiency, resilience, and regional trade connectivity	World Bank (2023); UNCTAD (2023)

Note. The indicators presented in Table 6 provide Libya-specific operational context and were used to support the interpretation of the MCDA criteria. Due to limited availability of standardized port-level datasets, the indicators were evaluated using internationally reported logistics assessments, maritime studies, and sustainability reports.

The operational characteristics presented in Table 6 support the lower MCDA performance scores assigned to Libya under the five evaluation criteria. The limited modernization of port infrastructure, low level of digital integration, and insufficient sustainability implementation explain the current performance gap compared with advanced logistics hubs such as Singapore, Rotterdam, Dubai, and Hong Kong.

However, Libya's current limitations also indicate substantial transformation potential. The country's strategic Mediterranean location, extensive coastline, existing port infrastructure, and significant renewable energy resources provide a foundation for future logistics modernization. Ports such as Misurata, Tripoli, and Benghazi could serve as key locations for implementing smart-port technologies, renewable-energy systems, digital customs platforms, and circular logistics initiatives.

Accordingly, the Libya-specific operational profile complements the international benchmarking approach by providing local context while maintaining consistency with the AHP–MCDA evaluation framework. The integration of these indicators strengthens the empirical basis of the study and improves the interpretation of Libya's current performance and future transformation scenarios.

4.7 Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the robustness of the proposed AHP–MCDA framework and determine the influence of criteria weighting variations on the final ranking outcomes.

Each criterion weight was individually modified by ±10%, while the remaining criteria weights were proportionally adjusted to maintain the normalization condition:

$$\sum_{j=1}^{n} w_j = 1$$

The sensitivity analysis examined the effects of weight variations on:

- The overall MCDA composite scores;
- The relative ranking of Libya and international benchmark logistics hubs;
- The stability of the identified transformation priorities.

The results demonstrated that Libya's ranking remained stable under all tested scenarios, with only minor variations in the calculated composite scores. No significant changes were observed in the relative position of the evaluated alternatives, confirming that the conclusions of the study are robust and not dependent on a single weighting configuration.

The sensitivity results further support the reliability of the proposed framework for evaluating sustainable logistics transformation pathways, particularly regarding the potential impacts of smart-port development, renewable-energy integration, digitalization, and circular economy strategies on Libya's future logistics competitiveness.

5. COMPARATIVE ANALYSIS

Table7. Normalized Global Logistics Performance Criteria Comparison

Country / Logistics Hub	Operational Efficiency	Sustainability Performance	Digitalization Level	Cost Efficiency	Circular Economy Integration
Singapore	0.95	0.90	0.95	0.80	0.88
Rotterdam	0.93	0.92	0.92	0.85	0.94
Dubai	0.85	0.75	0.87	0.90	0.70
Hong Kong	0.88	0.78	0.90	0.82	0.75
Libya	0.30	0.25	0.20	0.40	0.25

Note. All values represent normalized dimensionless performance scores ranging from 0 (lowest performance) to 1 (highest performance). The values were derived from international logistics, maritime,

sustainability, and digital transformation indicators collected from World Bank (2023b), UNCTAD (2023), IMO (2020), IAPH (2022), and IRENA (2022).

Comparative Analysis Discussion

The comparative analysis highlights substantial performance disparities between Libya and leading global logistics hubs. The values presented in Table 1 were derived from normalized secondary indicators collected from international logistics, maritime, and sustainability datasets and aggregated using the proposed MCDA framework. The results reveal significant variations in infrastructure maturity, digital capabilities, governance effectiveness, and sustainability integration. Singapore and Rotterdam achieve consistently high scores across the evaluated criteria, demonstrating the benefits of long-term strategic investment in port modernization, advanced logistics systems, and sustainable development frameworks.

Singapore achieves the highest performance, particularly in operational efficiency and digitalization, due to its highly automated port operations, integrated trade facilitation platforms, and advanced logistics ecosystem. These capabilities support efficient cargo handling, reduced processing times, and strong global connectivity. Rotterdam also demonstrates strong performance, particularly in sustainability and circular economy integration, supported by renewable energy initiatives, industrial symbiosis strategies, and environmentally oriented port development programs.

Dubai and Hong Kong maintain competitive performance levels, with strengths in logistics connectivity, infrastructure development, and digital transformation. Their results reflect sustained investment in smart port technologies, multimodal transportation networks, and strategic positioning within global trade routes.

In comparison, Libya achieves considerably lower scores across several assessment criteria, particularly digitalization, sustainability performance, and circular economy integration. The results indicate significant structural challenges, including limited digital infrastructure, outdated port systems, insufficient sustainability implementation, and institutional barriers affecting logistics modernization. These findings are consistent with the identified development gaps in Libya’s logistics sector and emphasize the need for coordinated technological, infrastructural, and policy interventions.

Nevertheless, Libya’s current lower performance should not be interpreted solely as a weakness but as an indicator of significant improvement potential. The country possesses strategic advantages, including its Mediterranean geographic position, extensive coastline, renewable energy resources, and opportunities for port redevelopment. By adopting phased transformation strategies involving digital logistics platforms, renewable energy integration, smart port technologies, and circular economy practices, Libya has the potential to progressively narrow the performance gap with international logistics leaders.

6. RESULTS

Table 8. Overall logistics performance ranking based on the weighted MCDA model.

Country	MCDA Score
Singapore	0.92
Rotterdam	0.90
Hong Kong	0.88
Dubai	0.85
Libya (Current)	0.35
Libya (Projected)	0.78–0.85

Note. MCDA scores represent aggregated normalized performance values calculated using AHP-derived criterion weights and the Weighted Sum Model (WSM). Scores range from 0 (lowest performance) to 1 (highest performance).

Data source: Calculated by the authors based on normalized indicators derived from World Bank (2023b), UNCTAD (2023), IMO (2020), IAPH (2022), and IRENA (2022).
Note. Scores were calculated using the proposed AHP–MCDA framework based on five evaluation criteria: operational efficiency, sustainability performance, digitalization level, cost efficiency, and circular economy integration

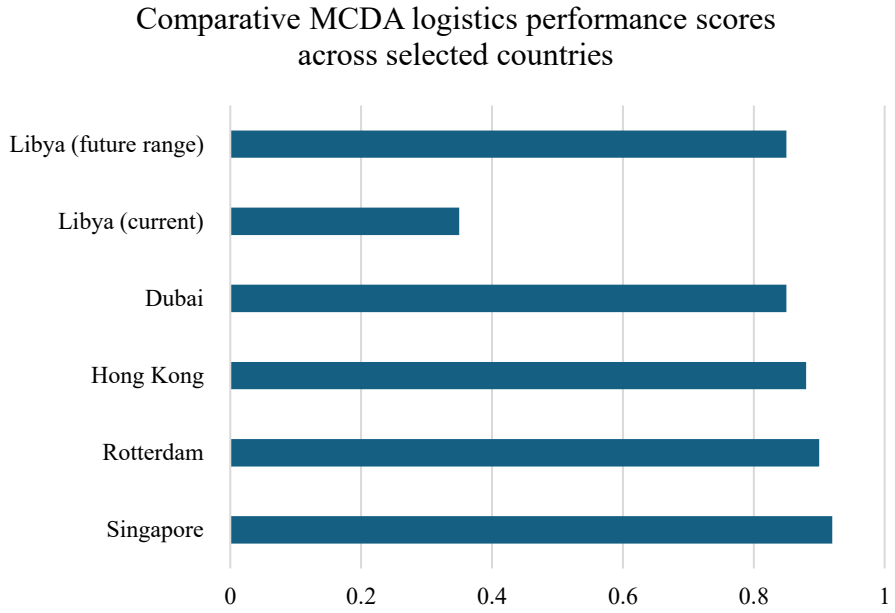


Figure 4. Comparative MCDA composite performance scores for international logistics hubs and Libya transformation scenarios.
The projected improvement reflects cumulative gains in digitalization, operational efficiency, sustainability, and governance rather than isolated infrastructure investments. The phased approach demonstrates that coordinated technological adoption and institutional reform can progressively reduce the performance gap between Libya and internationally recognized logistics hubs. Although the projected scores represent a scenario rather than a forecast, the analysis demonstrates that strategic investment combined with effective policy implementation could substantially enhance Libya's logistics competitiveness and strengthen its integration into regional and global supply chains.

7. TRANSFORMATION SCENARIOS

Table 9. Strategic transformation pathway for sustainable logistics development in Libya.

Phase	Time Horizon	Key Strategic Developments
Phase 1	0–5 years	Digital customs systems, smart-port pilot projects, solar-energy infrastructure, logistics data integration
Phase 2	5–10 years	AI-supported logistics optimization, hydrogen-based logistics applications, blockchain systems, multimodal transport integration
Phase 3	10+ years	Digital twin port systems, circular economy logistics ecosystem, renewable-energy-supported maritime hubs

Note. The transformation phases were developed based on scenario analysis results and international smart-port, sustainability, and energy-transition practices reported by IMO (2020), UNCTAD (2023), IAPH (2022), and IRENA (2022).

The proposed transformation roadmap presents a phased strategic pathway for Libya's long-term logistics modernization, derived from the scenario analysis findings and aligned with the projected MCDA performance improvements. The roadmap integrates technological advancement, sustainability objectives, and operational enhancement through a progressive implementation strategy.

The first phase focuses on establishing the institutional and technological foundations for transformation through digital customs systems, improved information exchange, and pilot smart-port applications. These initiatives are expected to enhance transparency, reduce administrative delays, strengthen governance, and improve operational coordination.

The second phase emphasizes advanced digital transformation through artificial intelligence, blockchain-enabled logistics coordination, and multimodal infrastructure integration. These technologies support predictive decision-making, optimize resource allocation, enhance supply chain resilience, and improve overall logistics efficiency.

The third phase represents a mature and sustainable logistics ecosystem characterized by digital twin technologies, circular economy principles, renewable-energy-supported port infrastructure, and low-carbon maritime operations. This final stage reflects the long-term vision of a resilient, digitally integrated, and environmentally sustainable logistics sector capable of significantly improving Libya's competitiveness within regional and global trade networks.

8. DISCUSSION

The findings demonstrate that substantial disparities exist between Libya and leading international logistics hubs across all evaluated performance dimensions. The MCDA results indicate that operational efficiency, digitalization, sustainability performance, governance quality, and circular economy integration collectively determine the competitiveness and resilience of modern logistics systems. Libya's comparatively low composite score reflects systemic challenges associated with fragmented institutional governance, limited infrastructure modernization, insufficient digital transformation, and weak integration of sustainable logistics practices.

The results are consistent with the World Bank Logistics Performance Index, which identifies infrastructure quality, customs efficiency, institutional effectiveness, and logistics competence as fundamental determinants of national logistics performance (World Bank, 2023b). Similarly, the Review of Maritime Transport published by the United Nations Conference on Trade and Development (UNCTAD, 2023) highlights digitalization, automation, and smart-port technologies as essential drivers of port efficiency, supply-chain resilience, and international trade competitiveness.

The comparative analysis further supports findings reported in Mediterranean port studies, which attribute differences in logistics performance primarily to governance quality, investment capacity, technological adoption, and institutional coordination (Hua et al., 2020; Fancello et al., 2021). The consistently higher scores achieved by Singapore, Rotterdam, Dubai, and Hong Kong demonstrate the importance of coordinated policy frameworks, long-term infrastructure investment, and continuous digital innovation in developing globally competitive logistics systems.

The scenario analysis indicates that Libya possesses considerable potential for logistics transformation despite its current limitations. The country's strategic Mediterranean location, together with significant renewable energy resources and existing port infrastructure, provides favorable conditions for implementing smart-port technologies, renewable-energy systems, and circular economy practices. The projected improvements in MCDA performance demonstrate that phased investments in digital customs systems, artificial intelligence, blockchain applications, renewable-energy infrastructure, and governance reform could substantially improve operational efficiency, environmental sustainability, and long-term competitiveness.

From a methodological perspective, this study contributes to the sustainable logistics literature by integrating the Analytic Hierarchy Process (AHP) with Multi-Criteria Decision Analysis (MCDA) to evaluate logistics systems using five complementary performance dimensions: operational efficiency, sustainability performance, digitalization level, cost efficiency, and circular economy integration. Unlike many previous studies that examine these dimensions independently, the proposed framework provides a transparent and comprehensive decision-support tool for benchmarking logistics systems and evaluating future transformation pathways.

The proposed framework also offers practical value for policymakers, port authorities, infrastructure planners, and investment agencies by supporting evidence-based decision-making for sustainable logistics modernization. Although the analysis focuses on Libya, the methodology can be adapted to other emerging economies seeking to improve logistics performance while simultaneously advancing digital transformation, environmental sustainability, and long-term economic resilience.

9. LIMITATIONS

Several limitations should be considered when interpreting the findings of this study.
First, the analysis relies primarily on internationally recognized secondary datasets because comprehensive, standardized, and publicly accessible operational logistics data for Libya remain limited. Although these datasets provide reliable international benchmarking, they may not fully capture local operational conditions, institutional characteristics, infrastructure constraints, or short-term performance variations within Libyan ports.

Second, the weighting of evaluation criteria was based on expert judgment using the Analytic Hierarchy Process (AHP). While the expert selection process followed established methodological guidelines and the consistency ratio satisfied the recommended acceptance threshold ($CR < 0.10$), some degree of subjectivity remains inherent in expert-based decision-making.

Third, the projected transformation scenarios represent strategic planning exercises rather than predictive forecasts. The estimated future performance improvements assume successful implementation of infrastructure investment, institutional reform, digital transformation, renewable-energy deployment, and supportive government policies. Consequently, actual outcomes may vary depending on political, economic, financial, and technological conditions.
Finally, empirical validation using primary operational data was beyond the scope of this study. Future research should strengthen the proposed framework through the collection of primary field data, port-level operational statistics, stakeholder interviews, real-time digital logistics indicators, and dynamic simulation models. Integrating these data sources would improve model validation, increase analytical precision, and enhance the practical applicability of sustainable logistics assessment in Libya and other emerging economies.

10. CONCLUSION

This study developed an integrated Analytic Hierarchy Process–Multi-Criteria Decision Analysis (AHP–MCDA) framework to evaluate the sustainability and operational efficiency of Libya's logistics sector relative to leading international logistics hubs, including Singapore, Rotterdam, Dubai, and Hong Kong. By integrating operational efficiency, sustainability performance, digitalization level, cost efficiency, and circular economy integration within a unified evaluation framework, the study provides a comprehensive assessment of Libya's current logistics performance and future transformation potential.

The comparative analysis demonstrates that Libya currently exhibits a significant competitiveness gap, primarily resulting from limited digital infrastructure, fragmented governance, insufficient sustainability integration, and underinvestment in modern logistics systems. In contrast, the benchmark logistics hubs

consistently achieve superior performance through coordinated governance, advanced digital technologies, smart-port implementation, renewable-energy adoption, and environmentally sustainable operational practices.

The scenario analysis further indicates that Libya possesses substantial opportunities for long-term logistics transformation. Strategic investments in digital customs systems, smart-port technologies, renewable-energy infrastructure, artificial intelligence, blockchain-enabled logistics management, and circular economy initiatives could significantly improve operational efficiency, environmental sustainability, and international competitiveness. These findings suggest that coordinated institutional reform and technology-driven modernization are essential prerequisites for developing a resilient and sustainable national logistics system.

From a policy perspective, the study recommends prioritizing five strategic actions: (1) modernization of port governance and institutional coordination; (2) implementation of integrated digital customs and smart-port technologies; (3) expansion of renewable-energy infrastructure within port operations; (4) adoption of circular economy principles to improve resource efficiency and reduce environmental impacts; and (5) establishment of long-term investment strategies that promote sustainable logistics development and regional trade integration.

Methodologically, this research contributes to the literature by demonstrating the applicability of an integrated AHP–MCDA framework for evaluating sustainable logistics systems using multiple performance dimensions within a transparent decision-support model. The proposed framework offers practical value for policymakers, port authorities, and infrastructure planners by supporting evidence-based planning and strategic investment decisions. Furthermore, the methodology may be adapted to evaluate logistics modernization initiatives in other emerging Mediterranean and North African economies.

Future research should extend this work through the incorporation of primary operational datasets, larger expert panels, real-time logistics performance indicators, dynamic simulation models, and longitudinal assessments of logistics transformation. Such developments would strengthen empirical validation, improve forecasting capability, and enhance the applicability of the proposed framework for supporting sustainable logistics policy and infrastructure planning.

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