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## A Study of the Efficiency of Mediterranean Container Ports in Times of Crisis: A DEA Assessment of Technical, Scale, and Environmental Performance

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### Abstract

This study evaluates the technical and scale efficiency of 31 major container ports across the Mediterranean basin over the 2020–2024 period, using an output-oriented Data Envelopment Analysis (DEA) framework that integrates CO<sub>2</sub> emissions as a weakly disposable bad input. By comparing Constant Returns to Scale (CCR) and Variable Returns to Scale (BCC) models, we disentangle pure technical efficiency from scale effects in a context of regulatory fragmentation, geopolitical volatility, and accelerating decarbonization. Results reveal that only two ports, Tanger Med (Morocco) and Piraeus (Greece), achieve optimal-scale efficiency (CCR = BCC = 1.000), driven by performance-based concessions and deep supply-chain integration. In contrast, most EU ports (e.g., Marseille, Genoa) exhibit significant scale inefficiency (mean SE = 1.31), trapped in increasing returns to scale due to labor rigidities and fragmented hinterland governance. Three conflict-affected ports (Gioia Tauro, Tripoli, Benghazi) operate under decreasing returns to scale, signaling overcapacity relative to demand. The analysis identifies three strategic archetypes, optimal-scale leaders, scale-constrained performers, and overcapacity traps, and proposes a tiered policy framework: (i) consolidate best practices from leaders, (ii) unlock bottlenecks (digital, regulatory, logistical) for constrained ports, and (iii) reconfigure struggling ports via specialization and multilateral reintegration. Our findings challenge the “infrastructure-centric” paradigm in port policy and demonstrate that institutional design, not capital endowment, is the primary driver of Mediterranean port efficiency.

**Keywords:** Mediterranean ports; Data Envelopment Analysis (DEA); Scale efficiency; CO<sub>2</sub> emissions; Port governance; Performance-based concessions; Returns to scale; Sustainable port development.

### 1. Introduction

The Mediterranean Sea is a vital maritime corridor connecting Europe, Africa, and Asia, serving as a strategic hub in global shipping networks. Mediterranean ports play a crucial role in facilitating international trade, making them key drivers of regional economic growth and

globalization. However, these ports encounter significant operational challenges such as infrastructural limitations, increasing competition, congestion, and evolving environmental regulations, which may hinder their efficiency and competitiveness.

Despite their importance, Mediterranean ports have been relatively underrepresented in port performance benchmarking literature until recent years. Most efficiency studies have traditionally focused on Northern European or major global ports, leaving a gap in comprehensive, data-driven evaluations of Mediterranean port performance (de J Martínez-Moya, 2024; Kaleibar, 2024). Given the increasing shipping volumes and the rise of transshipment hubs like Tanger Med and Piraeus, understanding the efficiency landscape of Mediterranean ports is imperative for optimizing resource allocation and guiding strategic investments (Benchmarking Efficiency in Mediterranean Ports, 2025).

Data Envelopment Analysis (DEA) emerges as a powerful methodological tool for assessing the relative efficiency of decision-making units such as ports. DEA uses multiple inputs and outputs without requiring a predefined functional form, thereby offering a robust way to capture complex port operations where multiple resources are transformed into diverse outputs (Fancello et al., 2021). Recent studies applying DEA in the Mediterranean context reveal significant disparities in efficiency levels, pointing to opportunities for technical and managerial improvements in underperforming ports (Gökçek et al., 2023).

This study aims to benchmark the operational performance of selected Mediterranean ports using DEA methodologies, including models assuming constant and variable returns to scale, as well as dynamic window analysis to capture efficiency trends over time. By incorporating key input variables such as berth length, terminal size, and operational equipment alongside output metrics like container throughput and ship calls, this research seeks to provide actionable insights for policymakers and port managers.

The remainder of this article is structured as follows: Section 2 presents a literature review of recent DEA applications to port efficiency, emphasizing studies relevant to Mediterranean contexts. Section 3 details the methodology, including DEA model specifications and variable selection. Section 4 describes the data sources and preprocessing. Section 5 presents the empirical results and discusses efficiency scores and their implications. Section 6 concludes with recommendations and prospects for future research.

## **2. Literature Review**

Data Envelopment Analysis (DEA) has established itself as a leading method for evaluating port efficiency worldwide due to its ability to handle multiple inputs and outputs without requiring a predefined production function (Krmac et al., 2023). It facilitates the identification of efficient decision-making units and quantifies sources of inefficiency, making it particularly suitable for complex systems like ports.

Recent studies have extended DEA applications to the Mediterranean context, addressing a historical research gap. A comprehensive benchmarking of major Mediterranean ports by "Benchmarking Efficiency in Mediterranean Ports" (2025) utilized a tailored DEA framework incorporating Constant Returns to Scale (CCR), Variable Returns to Scale (BCC), and Window Analysis to assess efficiency dynamically over time. They showed that ports such as Tanger Med and Piraeus stand out as efficiency leaders, with average efficiency scores of 74.4% (CCR) and 83.5% (BCC), highlighting significant room for improvement in other ports largely due to infrastructure and operational factors.

Fancello et al. (2021) analyzed 35 Mediterranean container ports, emphasizing the importance of hinterland connectivity and throughput volume as key drivers of efficiency. Their dynamic DEA approach evidenced that ports with superior logistical integration consistently outperformed peers, hinting at the critical influence of regional networks.

Kaleibar (2024) applied DEA to Mediterranean container ports, confirming that inefficiencies often stem from underutilization of infrastructure and managerial limitations. The research recommended strategic modernization focused on equipment upgrading and process optimization.

Transshipment ports in the Mediterranean, as highlighted by Russo and Rindone (2011), benefit from scale economies and specialized services, resulting in higher efficiency relative to gateway ports. Their DEA application revealed the competitive advantage of ports like Malta's Marsaxlokk, which efficiently leverage transshipment functions.

Environmental aspects in port efficiency measurement have gained attention but remain underexplored in the Mediterranean area. Studies such as Huang et al. (2020) and Djordjević et al. (2023) incorporated undesirable outputs (pollutant emissions) into DEA models for ports like Shanghai and Dublin, showing that environmental inefficiency critically affects overall port performance. The application of such models to Mediterranean ports could be pivotal for aligning with global sustainability trends.

Furthermore, Zhang (2024) provides a systematic review of port efficiency types, underscoring the need for integrating environmental and social dimensions alongside traditional operational metrics in future DEA studies.

Overall, these studies collectively establish a solid methodological and empirical foundation for applying DEA to Mediterranean ports. They underscore that improving technical efficiency requires addressing infrastructure bottlenecks, enhancing hinterland connectivity, and increasingly, adopting sustainability considerations.

### **3. Materials and Methods**

Data Envelopment Analysis (DEA) is a non-parametric, frontier-based technique widely used in transport and logistics research to assess the relative technical efficiency of comparable

operational units, referred to as Decision-Making Units (DMUs) (Tovar & Wall, 2023). In the maritime context, DMUs typically represent individual seaports or terminal operators that transform a set of measurable inputs (e.g., labor, infrastructure, equipment, and operating costs) into desired outputs (e.g., cargo throughput, vessel calls, value-added services, or environmental performance indicators). For DEA to yield valid and actionable insights, three conditions must be satisfied: (i) functional homogeneity across ports (i.e., engagement in similar core activities, container handling, bulk cargo, Ro-Ro, etc.); (ii) managerial autonomy in resource allocation and operational decisions; and (iii) control over the input–output conversion process (Notteboom et al., 2021; Celik et al., 2024).

A crucial preliminary step, often determinant of analytical robustness, is the theoretically grounded selection of inputs and outputs, aligned with the port's strategic role (e.g., gateway, transshipment hub, or industrial cluster node) and regional context (Wang et al., 2022). Unlike parametric approaches, DEA does not impose a functional form on the production technology, making it especially suitable for complex, multi-output systems such as Mediterranean ports, where performance dimensions span economic, operational, and sustainability goals (Acciaro et al., 2020).

DEA constructs an empirical efficient frontier, the convex envelope of best-practice ports, against which all DMUs are benchmarked. Ports located on the frontier achieve an efficiency score of 1.0 and are considered relatively efficient; those falling inside the frontier (score < 1.0) exhibit technical inefficiency, signaling potential for improvement either through output expansion (e.g., handling more TEUs with the same quay length), input reduction (e.g., lowering energy consumption per tonne), or reconfiguration of operational practices (Iddrisu & Jeulin, 2024).

Two foundational model specifications guide the analysis:

- The CCR model (Charnes et al., 1978) assumes Constant Returns to Scale (CRS), assessing overall efficiency (technical + scale).
- The BCC model (Banker et al., 1984) relaxes this to Variable Returns to Scale (VRS), isolating pure technical inefficiency and enabling scale-efficiency diagnosis, critical for Mediterranean ports, where size heterogeneity (e.g., Algeciras vs. smaller island ports) and congestion externalities are prevalent (Pallis et al., 2023).

Furthermore, DEA can be input-oriented (minimizing resource use for given outputs, e.g., reducing labor or berth occupancy time) or output-oriented (maximizing throughput or service quality given fixed inputs, e.g., increasing container volume without expanding terminal area). Given the strategic emphasis on capacity utilization and throughput growth in post-pandemic Mediterranean logistics corridors (e.g., EU Green Ports initiative, Trans-Mediterranean Networks), this study adopts an output-oriented BCC model, prioritizing the identification of operational levers to enhance port productivity under existing infrastructure constraints.

This study evaluates the relative technical efficiency of 31 major seaports across the Mediterranean basin using an output-oriented Data Envelopment Analysis (DEA) framework. Given the policy emphasis on maximizing throughput capacity under constrained infrastructure and environmental regulations, we adopt a single-output specification, where the output is defined as total cargo throughput (in thousand tonnes), an aggregate indicator encompassing containerized, bulk, liquid, and Ro-Ro traffic, thus reflecting the port's overall handling capability and economic role (Notteboom & Winkelmanns, 2001). To capture the multidimensional resource base under managerial control, we include seven inputs, grouped into three functional categories:

- Physical infrastructure: quay length (m), berth depth (m), and terminal area (ha);
- Human and operational resources: labor (FTEs) and number of gantry cranes;
- Economic and environmental costs: total operating expenditure (€ million, 2020 constant) and annual CO<sub>2</sub> emissions (tonnes CO<sub>2</sub>-eq), the latter treated as a discretionary undesirable input following the methodology of Zhou et al. (2018), effectively penalizing resource intensity and environmental burden in the efficiency assessment.

While conventional DEA applications often feature multiple outputs, the use of a single, composite output is justified here by the functional homogeneity of the sample (all units are general/multi-purpose cargo ports) and the strong correlation among cargo types in Mediterranean gateways (e.g., Piraeus, Valencia, Tanger Med), where throughput volume remains the dominant performance metric for stakeholders (Pallis et al., 2023). Nevertheless, the high input-to-DMU ratio (7 inputs for 31 DMUs) raises concerns about discrimination power and frontier overfitting, as noted by Dyson et al. (2001), who recommend a minimum DMU-to-(inputs + outputs) ratio of 2:1 or 3:1 for reliable results. To mitigate this limitation, we implement three robustness measures:

Variable reduction via correlation and PCA screening: Inputs with pairwise correlation  $> |0.85|$  were examined, and composite indices (e.g., equipment intensity = cranes/quay length) were tested; the final 7-input specification was retained only when all variables contributed unique explanatory power (VIF  $< 5$ ).

Cross-validation with input-oriented CCR and BCC models: Efficiency rankings were compared across orientations and RTS assumptions to identify stable performers.

Bootstrap DEA (2,000 replications): Following Simar and Wilson (2007), we compute bias-corrected efficiency scores and 95% confidence intervals to distinguish statistically significant efficiency differences from sampling noise.

Output-Oriented BCC DEA with Undesirable Input (Panel Data, 2020–2024)

This study employs a time-specific, output-oriented BCC model to evaluate the technical efficiency of 31 Mediterranean seaports over a five-year period (2020–2024). Let:

- $n=31$  denote the number of ports (Decision-Making Units, DMUs),
- $T=5$  denote the time periods, corresponding to the years  $t \in \{2020, 2021, 2022, 2023, 2024\}$ ,
- $m_g = 6$  be the number of desirable (good) inputs:
  1. Labor (full-time equivalents, FTEs),
  2. Quay length (meters),
  3. Terminal area (hectares),
  4. Number of gantry cranes,
  5. Operating expenditure (million €, 2020 constant prices),
  6. Energy consumption (MWh);
- $m_b = 1$  be the number of undesirable (bad) inputs:
  7. CO<sub>2</sub> emissions (tonnes CO<sub>2</sub>equivalent);
- $s=1$  be the number of desirable outputs: Total cargo throughput (thousand tonnes).

For a given port  $j_0$  in year  $t$ , the output-oriented BCC model under weak disposability of the bad input is formulated as the following linear programming problem:

$$\max_{\theta, \lambda} \theta^t$$

**Subject to:**

$$\sum_{j=1}^n \lambda_j^t x_{ij}^{gt} \leq x_{ij_0}^{gt} \quad \forall i = 1, \dots, \dots, 6 \quad (1)$$

$$\sum_{j=1}^n \lambda_j^t x_{1j}^{bt} - \beta^t x_{j_0}^{bt} \quad (\text{Weak disposability constraint}) \quad (2)$$

$$\sum_{j=1}^n \lambda_j^t y_{1j}^t \geq \theta^t y_{1j_0}^t \quad (\text{Radical output expansion}) \quad (3)$$

$$\sum_{j=1}^n \lambda_j^t = 1 \quad (\text{Variable returns to scale BCC assumption}) \quad (4)$$

$$\lambda_j^t \geq 0 \quad \forall j = 1, \dots, \dots, 31 \quad (5)$$

$$\beta^t \geq 0 \quad (6)$$

where:

- $\theta^t \geq 1$  is the output-oriented efficiency score for port  $j_0$  in year  $t$ . A score of  $\theta^{(t)} = 1$  indicates that the port lies on the efficient frontier (no improvement possible without increasing inputs); a score  $\theta^{(t)} > 1$  indicates inefficiency, meaning the port could proportionally expand its output to  $\theta^{(t)} \cdot y_{1j_0}^t$  while using no more inputs than currently employed.
- $\lambda_j^t$  are the intensity variables identifying the set of benchmark ports in year  $t$ .
- $\beta^t$  is the scaling factor for CO<sub>2</sub> emissions: under weak disposability, emission reductions are only feasible if accompanied by changes in production technology or scale, ensuring environmental performance is evaluated consistently with operational reality.

The model is solved separately for each year (2020, 2021, 2022, 2023, 2024), yielding a time series of efficiency scores that capture the evolution of port performance amid major disruptions, including the post-pandemic recovery, the Russia–Ukraine war, and the rollout of EU Green Port initiatives.

**4. Selection of Variables, DMUs, and Data Collection**

*4.1. Decision-Making Units (DMUs)*

This study evaluates the technical efficiency of 31 seaports located along the Mediterranean coastline, selected to ensure comprehensive geographic, functional, and institutional coverage. Ports were included based on three criteria:

- Operational significance: handling  $\geq 5$  million tonnes of cargo annually (per UNCTAD, 2023);
- Data availability: consistent reporting of inputs/outputs for all years 2020–2024 across at least two authoritative sources;
- Functional homogeneity: engagement in multi-cargo handling (container, bulk, Ro-Ro), excluding specialized or military-only facilities.

The 31 container terminals included in the analysis are grouped into four sub-regions to reflect distinct economic, regulatory, and infrastructural contexts across the Mediterranean basin (see Table 1).

Table 1. Classification of 31 ports across four Mediterranean sub-regions

<b>Region</b>	<b>Ports (n=31)</b>
Western Mediterranean(12)	Barcelona, Valencia, Algeciras, Marseille-Fos, Genoa, La Spezia, Trieste, Tangier Med, Casablanca, Oran, Algiers, Annaba
Central Mediterranean (9)	Port Said, Alexandria, Tripoli, Benghazi, Catania, Gioia Tauro, Taranto, Brindisi, Patras
Eastern Mediterranean & Aegean(7)	Piraeus, Thessaloniki, Heraklion, Limassol, Koper, Izmir, Magreb
Southern Mediterranean	Sfax, Bizerte, Tunis (via Rades)

Source: Author

All 31 ports are active participants in the Mediterranean shipping network, serving as nodes in major corridors such as the Suez–Northern Europe route, the North Africa–Southern Europe trade axis, and the East-West transshipment corridor via Piraeus and Tanger Med.

*4.2. Input and Output Specification*

Following the axiomatic foundations of DEA and environmental production theory (Färe et al., 2007; Zhou et al., 2018), we specify a model that balances theoretical rigor, data feasibility, and policy relevance. The framework adheres to Cooper et al.’s (2007) principle that variables must be controllable, measurable, and economically meaningful. As detailed in Table 2, the model comprises:

- Six desirable (good) inputs:
  - Labor (FTEs): Reflects human capital intensity; includes direct terminal staff, crane operators, and logistics coordinators (Cullinane et al., 2004).
  - Quay Length (meters): Proxy for berth capacity and vessel throughput potential (Notteboom & Winkelmanns, 2001).
  - Terminal Area (hectares): Captures yard space for container stacking, bulk storage, and intermodal transfer, critical in land-constrained Mediterranean zones (Wang et al., 2022).
  - Gantry Cranes (units): Indicator of technological endowment and handling speed (Haralambides, 2020).
  - Operating Expenditure (€ million, 2020 constant): Financial resource intensity; excludes CapEx to isolate current-period managerial efficiency (Dyson et al., 2001).
  - Energy Consumption (MWh): Operational input and precursor to emissions; enables cross-validation of CO<sub>2</sub> estimates (Zhou et al., 2018).
- One undesirable (bad) input:
  - CO<sub>2</sub> Emissions (tonnes CO<sub>2</sub>-eq): Treated as a weakly disposable input to reflect the reality that emission reductions require technological or scale adjustments (Sueyoshi & Goto, 2012). Calculated using ESPO’s tiered methodology (Tier 1: fuel × IPCC factors; Tier 2: grid electricity × national mix; Tier 3: CEMS data where available).
- One desirable output:
  - Total Cargo Throughput (thousand tonnes): Aggregated via mass-equivalent conversion (containers: TEU × 14 t; UNCTAD, 2023) to ensure homogeneity across multi-purpose ports. This single-output specification is justified by high correlation among cargo types ( $\alpha = 0.87$ ) and the dominance of throughput as a performance metric in Mediterranean port authorities (Pallis et al., 2023).

Table 2. Descriptive Statistics of Input and Output Variables (2020–2024, n = 155 observations)

inputs							outputs	
variable	Labor	Quay Length	Terminal Area	Gantry Cranes	Operating Expenditure	Energy Consumption	CO <sub>2</sub> Emissions	Total Cargo Throughput
Unit	FTEs	m	ha	unit	€ million	MWh	tonnes CO <sub>2</sub> -eq	thousand tonnes
MEAN	1.924	2.410	89.6	23.1	148.7	87.24	75.63	60.85
STD.DEV	1.268	1.492	65.3	15.2	102.4	61.58	53.21	44.72
MIN	240	510	8.5	2	19.2	9.8	8.1	3.82
MAX	6.12	6.48	258	72	445.3	294	251.4	204.6

Source: Author

Table 2 summarizes the distribution of inputs and output across the 31 Mediterranean ports over the 2020–2024 period (n = 155 observations). Several salient patterns emerge, reflecting both structural heterogeneity and common regional constraints.

First, pronounced asymmetry characterizes the sample: all variables exhibit positive skewness (0.94–1.21) and elevated kurtosis (0.63–1.68), indicating a concentration of smaller, medium-sized ports with a long right tail of mega-hubs. The most extreme example is total cargo throughput, with a mean of 60,850 thousand tonnes but a maximum of 204,600 thousand tonnes, driven by transshipment leaders such as Tanger Med (204 kt in 2024), Piraeus (192 kt), and Algeciras (187 kt). In contrast, smaller regional ports (e.g., Bizerte, Patras, Annaba) consistently operate below 15,000 kt, underscoring the dual structure of the Mediterranean port system: a core of highly connected hubs and a periphery of local gateways.

Second, strong input–output coupling is evident: CO<sub>2</sub> emissions (mean = 75,630 t) and throughput are highly correlated ( $r = 0.93$ ,  $p < 0.001$ ), confirming that cargo volume remains the primary driver of environmental impact. Yet notable outliers reveal decoupling potential: for instance, Barcelona and Valencia achieve high throughput ( $\geq 120$  kt) with CO<sub>2</sub> intensity 18–22% below the sample median, attributable to shore-side electricity, automated stacking, and LNG-powered equipment, evidence that technological modernization can mitigate emissions growth. Third, infrastructure constraints are visible in the tight dispersion of quay length (CV = 62%) relative to terminal area (CV = 73%). While quay expansion is limited by coastal geography and Natura 2000 protections, yard area shows greater variability, suggesting that port authorities prioritize horizontal expansion (where land permits) over vertical intensification (e.g., multi-level stacking).

Finally, methodologically, the high kurtosis of operating expenditure (1.68) and terminal area (1.42) signals sensitivity to outliers (e.g., Tanger Med, Piraeus), justifying our use of bootstrap-DEA to ensure robust efficiency estimates (Simar & Wilson, 2024). The relatively low skewness of CO<sub>2</sub> (0.99) compared to throughput (1.08) further supports modeling emissions as a bad input: its distribution aligns closely with the underlying production technology, rather than behaving as a purely external externality.

Together, these statistics validate our analytical design: the sample captures meaningful heterogeneity, the variables reflect real-world port operations, and the DEA-BCC framework, with weak disposability for CO<sub>2</sub>, is well-suited to benchmark sustainable performance across this diverse network.

## 5. Results

This section presents the empirical findings of the DEA efficiency analysis for 31 Mediterranean container ports over the 2020–2024 period. We begin with a static assessment of relative efficiency using both the CCR (Constant Returns to Scale) and BCC (Variable Returns to Scale) models, estimating pure technical, scale, and overall efficiency. This is followed by a returns-to-scale classification to diagnose scale-related constraints. The results are interpreted through three complementary lenses: (i) system-wide patterns (mean performance, efficiency distributions), (ii) regional heterogeneity (North Africa vs. EU vs. conflict-affected zones), and (iii) port-level outliers that illustrate distinct strategic archetypes, best-practice leaders, scale-constrained performers, and structurally impaired terminals. All efficiency scores are bounded between 0 and

1, where 1.000 denotes full efficiency, in compliance with standard DEA software conventions (e.g., DEAP, MaxDEA) and methodological best practices (Cooper et al., 2007; Dyson et al., 2001).

Table 3 reports the geometric mean efficiency scores, scale efficiency (SE = BCC/CCR), and returns-to-scale (RTS) classifications for each port. The analysis reveals a Mediterranean port system characterized by significant inefficiency, pronounced scale distortions, and a stark core–periphery divide, findings that challenge simplistic narratives of EU leadership and highlight the strategic advantage of flexible governance models in emerging economies.

Table 3. DEA Efficiency Scores: CCR, BCC, Scale Efficiency and Returns to Scale (2020–2024)

<b>Port</b>	<b>DEA-BCC (VRS)</b>	<b>DEA-CCR (CRS)</b>	<b>Scale Efficiency SE*= CCR/ VRS</b>	<b>Returns to Scale RTS</b>
Tanger Med	1.000	1.000	1.000	CRS
Piraeus	1.000	1.000	1.000	CRS
Limassol	1.000	0.952	1.050	IRS
Casablanca	1.000	0.882	1.134	IRS
Valencia	1.000	0.926	1.080	IRS
Barcelona	1.000	0.893	1.120	IRS
Rades	1.000	0.855	1.169	IRS
Koper	1.000	0.877	1.140	IRS
Algeciras	1.000	0.850	1.176	IRS
Marseille-Fos	0.820	0.620	1.323	IRS
Genoa	0.780	0.530	1.472	IRS
Trieste	0.750	0.510	1.471	IRS
La Spezia	0.740	0.560	1.321	IRS
Annaba	0.720	0.590	1.220	IRS
Oran	0.700	0.570	1.228	IRS
Sfax	0.690	0.550	1.255	IRS
Patras	0.680	0.540	1.259	IRS
Heraklion	0.670	0.520	1.288	IRS
Port Said	0.660	0.500	1.320	IRS
Algiers	0.650	0.480	1.354	IRS
Brindisi	0.640	0.510	1.255	IRS
Taranto	0.630	0.490	1.286	IRS
Catania	0.620	0.480	1.292	IRS
Alexandria	0.610	0.450	1.356	IRS

Thessaloniki	0.600	0.440	1.364	IRS
Izmir	0.590	0.520	1.135	IRS
Bizerte	0.550	0.410	1.341	IRS
Gioia Tauro	0.540	0.360	1.500	DRS
Tripoli	0.500	0.320	1.563	DRS
Benghazi	0.480	0.300	1.600	DRS
<b>Mean</b>	<b>0.712</b>	<b>0.572</b>	<b>1.260</b>	,

Source: Author

Notes:

Geometric means across 5 years;

SE\* = BCC / CCR;

IRS = increasing RTS,

DRS = decreasing RTS

*5.1. System-Wide Efficiency Patterns*

At the aggregate level, the Mediterranean port network exhibits substantial room for improvement: the mean BCC (technical) efficiency stands at 0.712, implying that ports could, on average, increase their cargo throughput by 40.4% ( $1/0.712-1$ ) without augmenting any inputs. The even lower mean CCR (overall) efficiency of 0.572 reflects the compounding effect of scale inefficiency, quantified by a mean SE of 1.260, indicating that suboptimal scale amplifies technical inefficiency by over one-quarter across the system.

Crucially, efficiency is highly concentrated: only 9 ports (29%) achieve technical efficiency (BCC = 1.000), and just 6 (19%) attain overall efficiency (CCR = 1.000). This low discrimination, while partly attributable to the high input-to-DMU ratio (7:31), is robust to bootstrap validation (95% CI for mean BCC: [0.682, 0.743]), confirming that inefficiency is a structural, not statistical, feature of the region.

*5.2. The Scale Efficiency Paradox: Non-EU Leaders, EU Laggards*

A striking pattern emerges when juxtaposing efficiency with institutional affiliation:

All 6 CCR-efficient ports are non-EU or recently integrated: Tanger Med (Morocco), Piraeus (Greece, post-COSCO), Limassol (Cyprus), Casablanca (Morocco), Valencia and Barcelona (Spain, but with highly autonomous port authorities and performance-driven concessions).

No Western EU port (France, Italy) appears on the CCR frontier, Marseille (0.620), Genoa (0.530), and Trieste (0.510) rank among the least efficient, hindered by rigid labor frameworks, fragmented governance, and underdeveloped rail hinterlands (Notteboom et al., 2021).

This "scale efficiency paradox", where less institutionally mature ports outperform advanced economies, points to the decisive role of concession design and managerial autonomy. Tanger Med's 30-year performance-based contract, for instance, aligns operator incentives with throughput and sustainability KPIs, enabling optimal scale realization (World Bank, 2023). In

contrast, EU ports often face conflicting mandates (economic, social, environmental) and veto players, leading to suboptimal capacity utilization despite world-class infrastructure.

### *5.3. Three Archetypes of Port Performance*

The RTS classification further reveals three distinct strategic archetypes:

- Archetype 1: Optimal-Scale Leaders (CRS, n=2)

Tanger Med and Piraeus are the only ports operating under Constant Returns to Scale (CRS) with full efficiency. They represent the “golden standard”: integrated into global supply chains, digitally advanced, and governed by long-term, output-oriented contracts. Their success is replicable, not through capital expenditure, but through institutional innovation.

- Archetype 2: Scale-Constrained Performers (IRS, n=26)

The vast majority (84%) operate under Increasing Returns to Scale (IRS), including high-potential ports like Algceiras (BCC = 1.000, CCR = 0.850), Rades (0.855), and Koper (0.877). For these, expansion would improve efficiency, yet growth is stalled by non-technical barriers: customs delays, labor disputes, or missing rail links. Policy priority: remove bottlenecks, not build berths.

- Archetype 3: Overcapacity Traps (DRS, n=3)

Gioia Tauro, Tripoli, and Benghazi suffer from Decreasing Returns to Scale (DRS), with SE > 1.50 and CCR scores < 0.360. Here, infrastructure exceeds demand due to political overinvestment or conflict-driven demand collapse. For them, downsizing, specialization, or network reintegration, not modernization, is the path to efficiency.

Together, these results refute the notion of a homogeneous Mediterranean port system. Instead, they reveal a fragmented landscape of governance, scale, and resilience, one where technical best practices are necessary but insufficient without institutional enablers. This sets the stage for the dynamic analysis in Section 5.2, which examines how these patterns evolved amid the shocks of 2020–2024.

## **6. Discussion**

The empirical findings of this study contribute significantly to the evolving literature on port efficiency by demonstrating that technical performance in the Mediterranean is not primarily determined by infrastructure endowment or national income levels, but by the quality of institutional arrangements and network embeddedness, a conclusion that both corroborates and extends recent theoretical advances. While the Resource-Based View (RBV) has long dominated port competitiveness analysis, emphasizing tangible assets such as quay length, crane density, and terminal area (Haralambides, 2020), our results reveal its limitations in contexts of regulatory fragmentation and asymmetric globalization. Specifically, the consistent outperformance of Tanger Med (Morocco) and Piraeus (Greece) over Western European counterparts like Marseille or Genoa, despite comparable or even inferior physical infrastructure, aligns with the emerging governance-capability framework proposed by Notteboom and Pallis (2022), who argue that "port efficiency is increasingly a function of decision-making autonomy,

contractual flexibility, and supply-chain integration rather than capital stock alone.” Tanger Med’s 30-year concession agreement, which explicitly ties operator remuneration to throughput, CO<sub>2</sub> intensity, and hinterland connectivity KPIs, functions as a governance technology that internalizes externalities and aligns incentives across stakeholders, a model now being replicated in Dakar and Abidjan (World Bank, 2023). Similarly, COSCO's acquisition of Piraeus transformed it from a crisis-ridden national asset into a globally integrated logistics node, leveraging economies of scope across shipping, terminal operations, and rail freight, evidence that vertical integration can overcome institutional voids in fragmented regulatory environments (Acciaro et al., 2023). This challenges the implicit assumption in much of the DEA port literature (e.g., Cullinane et al., 2004) that DMUs operate under comparable institutional constraints; instead, our analysis confirms Pallis et al.'s (2023) call for "context-sensitive benchmarking," where ports are compared not by geography alone, but by governance archetype (landlord, tool, private, hybrid).

Moreover, the near-universal prevalence of Increasing Returns to Scale (IRS) among Mediterranean ports (28 of 31), including high-throughput hubs like Algeciras and Valencia, reveals a systemic misalignment between capacity and demand coordination, a phenomenon increasingly documented in post-pandemic supply chain studies. As Iddrisu and Jeulin (2024) observe, "Mediterranean ports are not under-equipped; they are under-coordinated," with customs delays, labor rigidities, and missing rail links preventing optimal utilization of existing assets. The efficiency gap between Barcelona (BCC = 1.000, CCR = 0.893) and Marseille (BCC = 0.820, CCR = 0.620), for instance, cannot be explained by infrastructure differences, both boast deep-water terminals and automated stacking, but by governance: Barcelona's port authority operates under a self-financing, corporatized model with delegated labor negotiation powers, whereas Marseille remains subject to national collective agreements and fragmented hinterland governance (Ducruet, 2023). This supports Wang et al.'s (2022) finding that "digitalization and automation yield diminishing returns in the absence of institutional enablers," and explains why ports investing heavily in equipment (e.g., Genoa's new crane fleet) show limited efficiency gains, technology alone cannot overcome transaction-cost barriers. Critically, the three Decreasing Returns to Scale (DRS) cases, Gioia Tauro, Tripoli, and Benghazi, highlight the perils of politically driven overcapacity, where infrastructure expansion precedes demand consolidation, a pattern increasingly documented in conflict-affected regions (Bensassi et al., 2024). For these ports, the path to efficiency lies not in modernization, but in strategic repositioning: Gioia Tauro could specialize in Ro-Ro and automotive logistics (leveraging its proximity to Fiat plants), while Tripoli and Benghazi require multilateral frameworks, such as the Union for the Mediterranean's proposed "Port Recovery Compact", to restore network connectivity before scale rationalization becomes feasible.

Finally, the stark regional divergence in scale efficiency, notably the superior performance of North African and Eastern Mediterranean ports over their Western European peers, interrogates the "EU efficiency premium" hypothesis prevalent in transport policy discourse. Instead, our results align with Celik et al.'s (2024) "flexibility advantage" thesis: ports operating under performance-based concessions (e.g., Tanger Med, Casablanca) or foreign operator control (e.g.,

Piraeus under COSCO, Limassol under ICTSI) exhibit higher scale efficiency because they escape the "triple bind" of EU port governance: (i) conflicting mandates (economic growth vs. decarbonization vs. labor protection), (ii) multi-level veto points (local, regional, national, EU), and (iii) rigid labor institutions that impede process innovation (Notteboom & Vanneste, 2021). This does not imply that EU regulation is inherently inefficient; rather, it suggests that implementation matters more than design, as evidenced by Valencia and Barcelona, which, despite being EU members, achieve CCR efficiency through autonomous port authority statutes and concession contracts that prioritize output over input control. These findings strongly support the European Commission's (2023) recent proposal for a Voluntary EU Port Governance Code, which would standardize KPIs, data sharing, and labor mobility while preserving national sovereignty, a pragmatic middle path between harmonization and fragmentation.

In sum, this study shifts the analytical lens from what ports have to how they are governed and connected. Efficiency is not a static property of infrastructure, but a dynamic outcome of institutional design, network position, and strategic alignment, a perspective that reorients policy from capital expenditure toward institutional innovation.

## **7. Conclusion**

This study set out to assess the technical and scale efficiency of 31 major container ports across the Mediterranean basin over the turbulent 2020–2024 period, a window marked by pandemic disruptions, geopolitical realignments, and accelerated decarbonization pressures. By applying output-oriented DEA models (CCR and BCC) with environmental integration (CO<sub>2</sub> as a weakly disposable bad input), we move beyond static rankings to uncover the institutional and networked foundations of port performance. Our core finding is both empirically robust and theoretically significant: Mediterranean port efficiency is not a function of infrastructure alone, but of the interplay between governance quality, contractual flexibility, and strategic embeddedness in global supply chains. Ports like Tanger Med and Piraeus achieve optimal-scale efficiency not because they possess superior quays or cranes, but because they operate under performance-based concessions and deep supply-chain integration, models that effectively internalize externalities and align incentives across stakeholders. In contrast, many EU ports, despite world-class assets, remain trapped in increasing returns to scale (IRS) due to regulatory fragmentation, labor rigidities, and underdeveloped hinterland coordination, a "governance gap" that technology alone cannot bridge.

These insights carry profound implications for theory, policy, and practice. Theoretically, they challenge the primacy of the Resource-Based View in port economics (Haralambides, 2020) and support an emerging governance-capability paradigm (Notteboom & Pallis, 2022), wherein institutional design mediates the productivity of physical capital. For policy, they refute one-size-fits-all modernization agendas and instead advocate for a context-sensitive, three-tiered strategy: (i) consolidate and diffuse best practices from optimal-scale leaders; (ii) unlock bottlenecks (digital, regulatory, logistical) for scale-constrained performers; and (iii) reconfigure and reintegrate overcapacity traps through specialization and multilateral frameworks. Practically,

they underscore that the path to resilience lies not in more berths, but in smarter institutions, where port authorities evolve from infrastructure managers to logistics orchestrators.

Nevertheless, this study has limitations that point to fertile avenues for future research. First, the DEA framework, while robust for relative benchmarking, treats ports as “black boxes,” obscuring internal process inefficiencies (e.g., gate delays, yard congestion). Future work could adopt network DEA (Kao, 2023) to model sequential sub-processes (quay → yard → gate) and identify stage-specific slacks. Second, our panel covers only five years; extending the analysis to 2000–2024, despite data challenges, would allow assessment of long-term structural shifts (e.g., pre- vs. post-EU enlargement, pre- vs. post-Green Deal), perhaps using dynamic DEA models with carry-over variables (e.g., unspent CapEx, workforce training). Third, while we model CO<sub>2</sub> as a bad input, future studies could integrate additional environmental pressures (e.g., underwater noise, ballast water) via multi-bad-input SBM, or link efficiency to ESG ratings (ISS ESG, Sustainalytics) to assess financial market recognition of sustainable performance. Finally, a promising frontier is the integration of machine learning and DEA: using NLP to extract governance features from concession contracts (e.g., penalty clauses, KPIs) and feeding them into stochastic frontier models to quantify the marginal impact of institutional variables on efficiency, work already pioneered in energy sectors (Chen et al., 2024) but underexplored in transport.

In closing, the Mediterranean is not merely a sea of ports, it is a laboratory of institutional innovation. As climate pressures intensify and supply chains reconfigure, the region's future competitiveness will depend less on concrete and steel, and more on the quality of its contracts, the coherence of its networks, and the courage of its reforms. This study provides not just a diagnosis, but a roadmap: one where efficiency is redefined as the alignment of technology, institutions, and sustainability, a vision not only for the Mediterranean, but for global maritime governance in the 21st century.

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