Benchmarking Efficiency in Mediterranean Ports: A DEA-Based Analysis of Connectivity and Operational Performance

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Abstract: This study investigates the operational performance of major Mediterranean ports through a tailored Data Envelopment Analysis (DEA) framework. Recognizing the underrepresentation of these ports in existing benchmarking studies, this research emphasizes both connectivity and efficiency. Utilizing advanced DEA methodologies—Constant Returns to Scale (CCR), Variable Returns to Scale (BCC) and Window Analysis—the study evaluates efficiency trends over time, providing actionable insights for enhancement. Key input variables such as terminal size, berth length and equipment count are analyzed alongside output metrics like annual container throughput to ensure a comprehensive assessment of port performance. The findings reveal significant efficiency disparities among Mediterranean ports, with transshipment hubs like Tanger Med and Piraeus achieving optimal efficiency scores due to strategic investments and infrastructure upgrades. Conversely, many ports operate below optimal levels, indicating opportunities for technical and managerial improvements. This research contributes substantially to the field by introducing a novel benchmarking framework tailored to the unique geopolitical dynamics of the Mediterranean region. It highlights the critical role of connectivity, infrastructure and technology in driving efficiency while offering a valuable foundation for policymakers and port authorities to implement targeted strategies that enhance competitiveness and foster sustainable growth.

1 INTRODUCTION

Maritime trade has long served as a fundamental pillar of global commerce and the establishment of supply chains worldwide, facilitating the transportation of vast quantities of goods across various regions. The combined advantages of cost-efficiency and reliability have positioned shipping as a primary driver of growth in the era of globalization, particularly in the Mediterranean area—a region of geopolitical gravity where shipping has expanded its market share relative to other European regions, as noted by the European Commission's Internal Market report. The Mediterranean container market expanded to reach 55 million TEUs in 2014, driven by the surge in world trade and higher containerization rates. Containerized cargo thrives in transfer hubs across the Mediterranean, while roll-on/roll-off (RoRo) services also play an important role, especially in Short Sea Shipping (SSS) (Beizhen, 2021). The region acts as a vital link, connecting South European ports with Africa, the Americas, Northern Europe and Asia.

Despite a substantial imbalance in cargo volume between the northern and southern Mediterranean due to differing economic development levels, Mediterranean ports have maintained their relevance on the global stage (Colombo & Soler Lecha, 2020). They have consistently accounted for approximately 9% of global container traffic over the past two decades. Enhanced connectivity reinforces these ports' competitive advantage by facilitating proximity to major shipping routes (Martinez-Moya et al., 2024), such as the Suez Canal and the Strait of

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Gibraltar, while also allowing for value-added services like warehousing and repackaging.

Ports at the Mediterranean's edge tend to perform better in global trade than in local contexts, with notable examples like Tanger Med, Port Said and Algeciras leveraging strategic locations. These ports capitalize on their proximity to important maritime corridors to support regional and global economies effectively.

The Mediterranean region, historically a vital channel for goods transportation, has gained increasing prominence in global trade, particularly with the strategic importance of the Suez Canal and the Strait of Gibraltar (Arvis et al., 2018). Despite its consistent share of approximately 9% in global container traffic over the last two decades, the region faces substantial imbalances in cargo volumes between its northern and southern ports, largely due to differing levels of economic development. This disparity underscores the need for comprehensive port performance assessments.

While Northern Mediterranean ports have benefited from economic and political stability, many southern Mediterranean ports remain less integrated into global trade networks. Furthermore, competition among ports has intensified as modern technological advancements and intermodal systems have reduced reliance on immediate hinterland cargo, creating new performance pressures (Pinto et al., 2017).

Previous research on port performance has often focused on Northern European ports, leaving Mediterranean ports underrepresented in benchmarking studies. The growing shipping volumes in the region and the emergence of transshipment hubs and gateways demand a rigorous, data-driven approach to assess the operational efficiency and competitiveness of Mediterranean ports. Addressing these gaps is essential for fostering balanced development and ensuring that Mediterranean ports remain integral to global supply chains.

Based on this research gap, this paper aims to benchmark the operational efficiency of major Mediterranean ports using a Data Envelopment Analysis (DEA) framework. This study seeks to provide a comprehensive assessment of port connectivity and performance, addressing critical gaps in regional benchmarking data. The primary objectives of the paper are: (1) To analyse connectivity patterns in the Mediterranean Sea, emphasizing the geopolitical and port-specific characteristics that shape port performance. (2) To address the underrepresentation of Mediterranean ports in performance benchmarking studies by employing a dynamic efficiency measurement approach based on panel data. (3) To develop and implement a tailored DEA model to evaluate the operational efficiency of major Mediterranean ports, including the selection of input-output variables and comparative analysis across model variations. (4) To investigate the relationship between key determinants, such as port infrastructure and location, and the efficiency scores obtained from the DEA model, providing actionable insights for port performance improvement.

This paper contributes to the field by applying a tailored DEA framework to benchmark the efficiency of major Mediterranean ports. It offers insights into port connectivity and operational performance while addressing the region's underrepresentation in existing benchmarking studies. By analysing key determinants of efficiency, the paper provides actionable findings that can guide policy and strategic improvements for port authorities and stakeholders in the Mediterranean.

2 LITERATURE REVIEW

2.1 Port Performance and Benchmarking

The performance of ports is assessed through various metrics and methodologies. Key performance indicators (KPIs) such as throughput in TEUs, berth utilization rates and service times are used widely to capture aspects of operational efficiency and productivity (Cullinane & Wang, 2010). Frontier analysis techniques, particularly DEA and Stochastic Frontier Analysis (SFA), have become prominent for benchmarking performance across ports (Cullinane & Wang, 2010). DEA, a non-parametric method, is popular for determining efficiency by comparing Decision-Making Units (DMUs) under the assumption of exact input-output relationships. It is commonly used to identify underperformance by establishing a best-practice frontier based on observed data.

Comparative studies on ports frequently categorize them by various attributes such as location, annual throughput and terminal characteristics. For example, studies using DEA models have segmented ports based on TEU volumes or distinguished between transshipment and gateway ports to understand performance differentials and the impact of specific port attributes. These benchmarking analyses often highlight important efficiency disparities, even among geographically proximate ports, due to differences in infrastructure, equipment and management practices.

In recent years, multi-step DEA approaches have been implemented, combining DEA with methods such as SFA to account for noise in data and enhance accuracy. For instance, studies comparing ports in developing countries with their counterparts in developed regions utilize hybrid models to isolate technical efficiency from environmental effects. The DEA-Malmquist index is also employed to track changes in productivity over time, addressing both technical and scale efficiencies.

Benchmarking port performance enables authorities to adopt best practices and focus on continuous improvement across multiple performance dimensions, including operational, financial, environmental and customer satisfaction metrics. These methodologies allow for the comparison of port operations in a structured manner, driving a competitive and systematic approach to efficiency improvements.

2.2 Key Performance Indicators (KPIs)

KPIs are established as quantifiable metrics used to evaluate port efficiency across various dimensions, including operational, financial and environmental aspects (Duru et al., 2020). Initially, port KPIs focused on operational aspects such as crane movements per hour and container throughput, providing a basis for comparative performance analysis among terminals. Over time, however, the scope of KPIs has expanded to include indicators that account for logistical, customer-oriented, and sustainability-related factors to reflect the evolving needs of global port stakeholders (Woo et al., 2011).

The framework for categorizing KPIs often considers both internal and external performance dimensions, as different stakeholders—such as port authorities, customers and environmental agencies—prioritize various aspects of port efficiency. Categories may include operational KPIs, like berth occupancy and average container dwell time, as well as financial KPIs, such as cost per TEU and revenue per ton managed.

Modern approaches to KPI development incorporate complex modelling techniques. For instance, tools like the fuzzy-Delphi method (Wang et al., 2014) and the Analytical Hierarchy Process (AHP) (Ha et al., 2019) are utilized to weigh and prioritize KPIs based on stakeholder importance, ensuring that the metrics align with strategic objectives across the operational landscape.

2.3 Benchmarking Methods

Benchmarking methods for port performance can be broadly classified into index methods, frontier analysis and process approaches (Bichou, 2013). Index methods often involve financial ratios, snapshot indicators and Total Factor Productivity (TFP), offering straightforward metrics, but limited in addressing comprehensive operational contexts.

Frontier analysis, encompassing DEA and SFA, remains one of the most widely applied techniques (De Borger B. et al., 2002). DEA employs linear programming to construct a non-parametric frontier, enabling the evaluation of multiple inputs and outputs without assuming specific functional relationships. Its variants, such as DEA-CCR for constant returns to scale and DEA-BCC for variable returns, allow for flexibility in capturing technical and scale efficiency. Meanwhile, SFA provides a parametric approach that incorporates stochastic factors to account for environmental influences and data variability (Chang & Tovar, 2014).

Advanced applications, like the Malmquist Productivity Index, integrate DEA to analyze productivity changes over time, distinguishing between technical efficiency improvements and technological advancements (Suárez-Alemán et al., 2015). Additionally, hybrid approaches combining DEA with methods like SFA or regression models enhance robustness by addressing the limitations of individual techniques.

Process approaches, including Total Quality Management (TQM) and perception surveys, contribute qualitative insights by incorporating stakeholder feedback and expert judgment. These approaches complement quantitative methods, ensuring a holistic assessment of port performance.

The selection of a suitable benchmarking methodology depends on the specific objectives, data availability and contextual constraints of the analysis. By employing these methods, researchers and practitioners can derive actionable insights to drive port efficiency and competitiveness (Feng et al., 2012).

3 METHODOLOGY

3.1 Benchmarking Framework

To systematically evaluate port performance, this study employs a comprehensive benchmarking framework, with Data Envelopment Analysis (DEA) as the primary methodology. DEA is a linear programming technique used to assess the efficiency of Decision-Making Units (DMUs) (Cooper et al., 2007). It constructs a non-parametric efficiency frontier based on multiple input and output variables, allowing for comparative benchmarking without requiring a predefined functional relationship (Mustafa et al., 2021). Two primary DEA models—Constant Returns to Scale (CCR) and Variable Returns to Scale (BCC)—are implemented. The CCR model assumes a fixed input-output ratio across all DMUs, while the BCC model introduces flexibility for scale efficiencies (Benicio & De Mello, 2019). This framework integrates methodologies such as the Malmquist Productivity Index to measure productivity changes over time and combines DEA with techniques like Stochastic Frontier Analysis (SFA) to enhance robustness against environmental factors and data variability. Key input variables include berth length, terminal area and equipment quantity, while output variables focus on container throughput and other operational metrics. The selection of variables is guided by expert screening and prior studies to ensure relevance in the benchmarking analysis. By leveraging this framework, the study aims to identify efficiency drivers and provide actionable insights for port performance optimization. This approach allows for examining both technical and scale efficiencies while accommodating diverse operational contexts. This revision maintains all critical references and information while making the text more concise and focused.

3.2 Dataset

The dataset used in this study includes detailed operational data from various Mediterranean ports, sourced from publicly accessible databases, port authorities' records and commercial maritime reports. Primary input variables encompass terminal dimensions, berth length and equipment count, while output variables include annual container throughput, expressed in TEUs. Figure 1 illustrates the relationship between input variables (e.g., terminal size, berth length, and equipment count) and output variables (e.g., annual throughput in TEUs) as utilized in the DEA model.

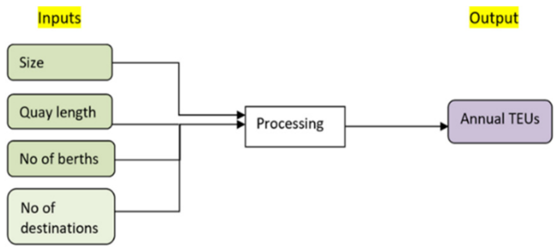

Figure 1: DEA Graph with Inputs and Outputs.

Supplementary information, such as the year of data capture and handling capacity, is used to ensure uniform benchmarking across diverse ports. These inputs were selected based on industry standards and prior benchmarking studies to allow accurate efficiency assessment across comparable contexts. Table 1 presents the key input-output variables for the DEA-CCR and DEA-BCC models, detailing the dimensions of the dataset across multiple ports.

Table 1: Input data for DEA-CCR & BCC.

Sample-Ports	(I) Size	(I) Berths	(I) Quay Length	(I) Int. Tr. Dest/tions	(O) An. Teus (2019)
Alexandria	200	4	732	47	851
Algeciras	306	9	4034	56	5125
Ambarli	95	6	2602	27	3104
Barcelona	1065	11	3000	56	3324
Casablanca	257	12	1500	42	6040
Genoa	700	6	1433	37	2621
Gioia Tauro	440	8	3391	8	2523
Haifa	158	4	1360	46	1470
Izmit (Evyap)	65	4	656	24	1715
La Spezia	150	8	1400	15	1409
Livorno	112	3	1858	27	789
Marsaxlokk	77	5	2801	40	2722
Marseilles	316	17	2798	41	1454
Mersin	112	9	1020	49	1854
Piraeus	220	9	2774	63	5648
Port Said	130	8	947	33	3816
Sines	151	6	1040	10	1420
Tanger Med	335	6	1200	55	4801
Valencia	456	11	3600	68	5439

3.3 Evaluation Metrics

Performance evaluation metrics focus on efficiency scores derived from DEA using both the CCR and BCC models. The study also employs technical efficiency and scale efficiency scores to distinguish managerial efficiency from size-driven advantages. Additionally, dynamic metrics like Window Analysis enable the comparison of port efficiency trends over time by considering each port as a distinct Decision-Making Unit (DMU) at different time intervals.

3.4 Procedures

The analysis follows a systematic application of DEA, beginning with the standard DEA-CCR and

DEA-BCC models to assess ports under constant and variable returns to scale. The Malmquist Productivity Index supplement this process to evaluate efficiency changes over time. For each port, DEA models are calibrated based on operational inputs and container throughput, while Window Analysis is applied for longitudinal efficiency comparison. The DEA Solver software facilitates the computation, allowing for consistent application of both CCR and BCC models across the dataset (Cooper et al., 2007).

4 EXPERIMENTAL SETUP AND BASELINE MODELS

4.1 Model Specifications

The analysis employs DEA models, specifically the output-oriented CCR (constant returns to scale) and BCC (variable returns to scale) approaches, to evaluate the relative efficiency of Mediterranean ports. The DEA framework incorporates inputs such as terminal size, quay length and the number of container berths, while the primary output is annual container throughput in TEUs. The study also includes time-dependent DEA through Window Analysis, treating each port as a different DMU across time periods. This enhances the discrimination power of the model, identifying trends in port performance over the observation period.

Key control variables are included to account for external factors influencing port efficiency. These variables include: (1) **Port connectivity**: Measured through the number of intermodal destinations served. (2) **Economic indicators**: Such as regional GDP and trade openness. (3) **Port size**: Categories based on terminal area to examine scale effects. These variables ensure that the DEA results accurately reflect operational efficiencies, minimizing biases caused by external and contextual differences among ports.

Baseline models include both standard DEA and its advanced variations for robust comparison:

- Standard DEA Models: CCR and BCC models to evaluate technical and scale efficiency.
- Window DEA Analysis: To capture dynamic performance trends over time.
- Two-Stage DEA: Integrating regression analysis in the second stage to investigate the impact of exogenous factors, such as port governance and hinterland connectivity.

Table 2 provides descriptive statistics for the input and output variables used in the DEA analysis, summarizing averages, minimums, and maximums for terminal dimensions and throughput.

Table 2: Descriptive Statistics of Variables.

Variable	Avg.	Min	Max	Std. Dev.
Terminal Area (hectares)	281.31	65.00	1065.00	248.74
No of berths (container)	7.68	3.00	17.00	3.44
Quay Length (meters)	2078.55	656.00	4034.00	1044.85
No of transshipment destinations	39.15	8.00	68.00	17.33
Annual Throughput (TEUs, 2019)	2953.94	789.00	6040.00	1722.09

5 RESULTS AND ANALYSIS

The results from the DEA analysis show average efficiency scores of 0.744 and 0.835 for the CCR and BCC models, respectively. This implies potential output increases of 62.64% for the CCR model and 36.87% for the BCC model, without requiring additional inputs. Table 3 summarizes the DEA results, highlighting that a substantial number of ports are operating below optimal efficiency levels.

For example, the BCC model identifies ten ports as efficient, while the CCR model identifies 7, indicating room for performance improvements among most ports. The analysis by port type and size shows that while transshipment ports tend to achieve higher efficiency, the statistical weight is not robust. An ANOVA test reveals that the efficiency differences based on TEUs are statistically important ($p = 0.005$), while those based on port type are not ($p = 0.064$). The three-group size comparison (small, medium, large) yields no statistically important differences, indicating that port size alone does not determine efficiency outcomes.

For temporal analysis, the Window Analysis method reveals stability in efficiency scores across most ports, with the notable exception of ports like Piraeus, which shows a consistent upward trend due to strategic improvements and investment. This method allows for nuanced insights into efficiency trends over time by treating each period as a different observation for each port. Table 4 presents the efficiency scores and ranks for ports under the BCC model, highlighting performance variations driven by variable returns to scale. In the reference set column in Tables 3 and 4, the ports that are used as reference points are used. These ports are being used as a scale for the inefficient ports to evaluate their efficiency. When the ports reach maximum efficiency, i.e. 1, their reference set is only themselves. The ports of Casablanca and Tanger Med are used more often than the others as reference ports, i.e., 8 times.

Table 3: DEA statistics, CCR-focused.

No	DMU	CCR-Score	CCR-Rank	Reference Set	Sum of Lambdas	BCC-Score	BCC-rank	CCR
1	Ambarli	1	1	{1}	1	1	1	Constant
2	Casablanca	1	1	{2}	1	1	1	Constant
3	Gioia Tauro	1	1	{3}	1	1	1	Constant
4	Marsaxlokk	1	1	{4}	1	1	1	Constant
5	Piraeus	1	1	{5}	1	1	1	Constant
6	Port Said	1	1	{6}	1	1	1	Constant
7	Tanger Med	1	1	{7}	1	1	1	Constant
8	Algeciras	0.8994	8	{2,7,5}	1,065	0.9254	11	DRS
9	Izmit (Evyap)	0.8836	9	{5,4}	0,529	1	1	IRS
10	Sines	0.8161	10	{2,3}	0,416	1	1	IRS
11	Valencia	0.768	11	{2,7}	1,351	0.9204	12	DRS
12	Genoa	0.6793	12	{2,7}	1,91	0.7384	13	DRS
13	La Spezia	0.5967	13	{2,3}	0,478	0.697	15	IRS
14	Mersin	0.5568	14	{4,6}	0,899	0.5653	16	IRS
15	Haifa	0.5174	15	{5,7}	0,531	0.7314	14	IRS
16	Barcelona	0.5151	16	{2,7}	1,174	0.5625	17	DRS
17	Livorno	0.3766	17	{5,7}	0,401	1	1	IRS
18	Alexandria	0.2903	18	{2,7}	0,592	0.4872	18	IRS
19	Marseilles	0.2374	19	{2,3}	1,512	0.2449	19	DRS
No of efficient DMUs		7				10		
Average efficiency		0.744				0.8354		

Table 4: DEA statistics, BCC-focused.

No	DMU	BCC-Score	BCC-Rank	Reference Set	Scale Efficiency	BCC
1	Ambarli	1	1	{1}	1	Constant
2	Casablanca	1	1	{2}	1	Constant
3	Gioia Tauro	1	1	{3}	1	Constant
4	Izmit (Evyap)	1	1	{4}	0.8836	IRS
5	Livorno	1	1	{5}	0.3766	IRS
6	Marsaxlokk	1	1	{6}	1	Constant
7	Piraeus	1	1	{7}	1	Constant
8	Port Said	1	1	{8}	1	Constant
9	Sines	1	1	{9}	0.8161	IRS
10	Tanger Med	1	1	{10}	1	Constant
11	Algeciras	0.9254	11	{2,7,10}	0.9719	Constant
12	Valencia	0.9204	12	{10}	0.8344	Constant
13	Genoa	0.7384	13	{1,2,4,10}	0.9199	IRS
14	Haifa	0.7314	14	{4,5,10}	0.7074	IRS
15	La Spezia	0.697	15	{1,2,9}	0.8546	IRS
16	Mersin	0.5653	16	{4,6,10}	0.9849	IRS
17	Barcelona	0.5625	17	{2,7}	0.9158	Constant
18	Alexandria	0.4872	18	{4,5,10}	0.5958	IRS
19	Marseilles	0.2449	19	{2,3}	0.9693	Constant

Table 5: Summary of DEA results.

Division		CCR	BCC	Scale Efficiency
DMU	Efficient	7 (37%)	10 (53%)	CRS
	Inefficient	12 (63%)	9 (47%)	DRS
	Total	19 (100%)	19 (100%)	IRS
Average Efficiency		0.744	0.835	0.885805

The results underscore the sensitivity of DEA to data variations and missing values, particularly with respect to underperforming ports. For example, data errors or omissions in terminal area and berth length measurements may affect efficiency scores. To address these limitations, methods such as SFA and super-efficient DEA could be integrated to adjust for data inaccuracies and enhance the robustness of findings. Future research could explore interval models and regional comparisons to refine benchmarks and expand insights.

6 DISCUSSION

The findings of this study highlight important disparities in the operational efficiency of Mediterranean ports, emphasizing the value of benchmarking practices in driving improvements. Ports such as Tanger Med and Piraeus demonstrate how targeted investments in infrastructure and technology can yield substantial efficiency gains, aligning operations with the demands of global supply chains. Their strategic use of location and optimized input-output relationships sets benchmarks for the region.

Conversely, many Mediterranean ports operate below potential efficiency levels, indicating the need for managerial and technical improvements. Focusing on pure technical efficiency—maximizing outputs from given inputs—is more critical than merely scaling operations. This includes adopting resource optimization through automation, smart terminal operations, and intermodal connectivity to mitigate bottlenecks, reduce idle time, and enhance throughput capacity. Ports that integrate such technologies perform better overall.

Intermodal connectivity also plays a pivotal role. Ports with robust links to rail, road, and inland waterways exhibit higher efficiency, showcasing the importance of seamless logistics. For southern Mediterranean ports, developmental and competitive challenges compared to northern counterparts could be addressed through enhanced hinterland connectivity. This would better integrate these ports into global trade networks and leverage their geographic advantages.

These findings underscore the necessity for port managers to optimize terminal layouts, invest in advanced equipment, and adopt data-driven decision-making. Collaborative efforts among ports can generate synergies, sharing best practices and infrastructure. Policymakers must support these advancements through financial incentives and favourable regulations, enabling operational improvements. For instance, encouraging sustainable practices, such as energy-efficient technologies, addresses both efficiency and environmental concerns.

While the study provides valuable insights, its reliance on DEA methodology introduces limitations, particularly its sensitivity to data quality. Future research could address this by integrating stochastic methods like SFA, which account for random variations and external influences. Additionally, leveraging advanced data collection tools, such as IoT sensors, could enrich datasets with real-time performance metrics. Addressing these aspects would yield a more comprehensive understanding of port operations.

Overall, this study emphasizes the importance of strategic investments, technological innovation, and regional collaboration in driving port efficiency. Ports adopting dynamic benchmarking approaches and prioritizing continuous improvement are better positioned to remain competitive in the evolving global trade landscape.

7 CONCLUSION

This study provides a comprehensive analysis of Mediterranean port performance using DEA models, highlighting critical insights into efficiency drivers and benchmarking practices. Key findings include: (a) **Efficiency Scores,** the average efficiency across the ports analysed is 74.4% (CCR) and 83.5% (BCC), indicating significant room for improvement. Ports such as Tanger Med, Piraeus, and Marsaxlokk consistently achieve efficiency frontier status. (b) **Role of Port Type and Scale,** transshipment ports demonstrate higher efficiency levels compared to gateway ports, leveraging economies of scale and strategic location advantages. However, the size of the port was found to have an unimportant impact on efficiency. (c) **Temporal Trends,** Window Analysis revealed stable efficiency scores over time, with notable improvements in ports undergoing strategic investments. These results emphasize the importance of managerial practices and technological adoption in achieving and sustaining efficiency. The implications of this research extend beyond individual ports, providing actionable insights for regional and global port management.

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