Evaluating the Operational Efficiency of Tanger-Med Port as a Mediterranean Transshipment Hub: A DEA-BCC Model with Bootstrap Robustness Analysis

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ABSTRACT: *The increasing competition among Mediterranean transshipment ports has highlighted the importance of operational efficiency evaluation for improving resource utilization and maintaining long-term competitiveness. Tanger-Med Port has expanded rapidly and become increasingly integrated into international container shipping networks, yet the extent to which its resource investments have translated into operational efficiency requires quantitative investigation. This study evaluates the efficiency of Tanger-Med Port relative to representative Mediterranean transshipment ports using Data Envelopment Analysis (DEA) combined with bootstrap robustness analysis. An input-oriented DEA-BCC model measures pure technical, overall technical, and scale efficiency from multiple infrastructure and operational indicators for 2018–2024, and bootstrap DEA corrects potential bias and verifies the robustness of the rankings. The results show that Tanger-Med achieves a high level of operational efficiency among Mediterranean transshipment centres, benefiting from effective resource utilization, strategic location, and appropriate capacity development. Efficiency improved continuously following infrastructure expansion, and the bootstrap results confirm the stability of Tanger-Med's competitive position after bias correction. By integrating DEA-BCC and bootstrap techniques, the study offers a more reliable assessment of transshipment hub performance and practical implications for port authorities on infrastructure planning, operational optimization, and sustainable development.*

KEYWORDS - *Bootstrap DEA, Container port efficiency, Data envelopment analysis, Tanger-Med Port, Transshipment hub*

I. Introduction

The rapid transformation of global container shipping networks has intensified competition among international transshipment ports. As shipping alliances increasingly concentrate vessel services at major hubs, port competitiveness is no longer determined solely by cargo-handling capacity but also by the ability to efficiently utilize infrastructure, equipment, labor, and operational resources. For transshipment ports, which primarily compete through connectivity and container transfer performance rather than regional cargo generation, operational efficiency has become a critical factor influencing their long-term strategic position.

The Mediterranean region represents one of the world's most important maritime corridors, connecting major trade routes between Asia, Europe, and Africa. Several ports, including Algeciras, Malta Freeport, Piraeus, Valencia, and Tanger-Med, compete to attract global shipping services and strengthen their roles within international logistics networks. However, increasing infrastructure investment does not necessarily guarantee competitive advantage. Large terminal expansions may generate inefficiency if additional capacity is not effectively converted into operational outputs. Therefore, quantitative efficiency evaluation is essential for determining whether port resources are being utilized effectively.

Tanger-Med Port provides an important case for examining these issues. Located near the Strait of Gibraltar, Tanger-Med has rapidly developed into a major Mediterranean transshipment hub through continuous investment in container terminals, logistics infrastructure, and maritime connectivity. Its strategic location and integration into global shipping networks have significantly enhanced its

competitive position. Nevertheless, whether Tanger-Med's infrastructure expansion has resulted in superior operational efficiency compared with competing Mediterranean hubs remains an empirical question requiring systematic investigation.

Data Envelopment Analysis (DEA) has been widely applied to evaluate port efficiency because it can handle multiple inputs and outputs without requiring a predefined production function. However, conventional DEA models estimate efficiency based on a deterministic frontier constructed from observed decision-making units, which may lead to biased efficiency scores. Bootstrap DEA methods have been developed to address this limitation by estimating the statistical uncertainty of efficiency measurements and providing more reliable benchmarking results. Despite the increasing application of DEA approaches in port research, limited studies have integrated DEA-BCC and bootstrap robustness analysis to evaluate emerging Mediterranean transshipment hubs.

Therefore, this study aims to evaluate the operational efficiency of Tanger-Med Port compared with representative Mediterranean transshipment centres during the period 2018–2024. Specifically, this research applies an input-oriented DEA-BCC model to measure technical efficiency, pure technical efficiency, and scale efficiency, and subsequently employs bootstrap DEA analysis to examine the robustness of efficiency estimates.

This study contributes to the literature in three ways. First, it develops a more reliable efficiency evaluation framework by integrating DEA-BCC with bootstrap correction. Second, it provides empirical evidence on Tanger-Med's efficiency performance within the competitive Mediterranean transshipment network. Third, it examines the dynamic evolution of efficiency during a period of significant infrastructure expansion, providing practical implications for port development strategies.

The remainder of this paper is organized as follows. Section 2 reviews relevant literature on port efficiency evaluation and bootstrap DEA methods. Section 3 presents the methodology and data. Section 4 discusses the empirical results. Section 5 concludes the study and provides policy implications.

II. Literature Review

2.1 Concepts and Determinants of Port Efficiency Measurement

Ports serve as critical nodes in global maritime transportation networks, connecting inland transportation systems with international shipping routes. As competition among container ports has intensified, evaluating operational efficiency has become increasingly important for understanding whether ports can effectively transform available resources into desirable operational outcomes.

Port efficiency differs from traditional performance indicators such as throughput volume or vessel calls because it considers the relationship between inputs and outputs. A port with high throughput does not necessarily operate efficiently if its performance is achieved through excessive resource consumption. Therefore, efficiency analysis focuses on the extent to which ports utilize available resources, including infrastructure, equipment, labor, and operational capacity, to generate outputs such as container handling services and vessel operations.

Previous studies have identified several factors influencing port efficiency. Infrastructure availability, terminal capacity, cargo-handling equipment, labor productivity, and operational management are commonly considered important determinants. However, the relationship between these resources and port performance is complex because ports operate under different geographical, economic, and operational conditions. Consequently, efficiency evaluation requires analytical approaches capable of simultaneously considering multiple inputs and outputs.

Among various efficiency measurement techniques, Data Envelopment Analysis (DEA) has become one of the most widely adopted approaches in port efficiency research because it does not require a predefined functional relationship between inputs and outputs. By constructing an efficiency frontier based on observed decision-making units (DMUs), DEA enables relative efficiency comparisons among ports with different operational characteristics.

2.2 DEA Applications in Port Efficiency Evaluation

DEA is a non-parametric efficiency measurement method initially introduced by Charnes et al. [1]. The approach evaluates the relative efficiency of multiple decision-making units by comparing the

weighted combination of outputs with the weighted combination of inputs. Because ports typically involve multiple resources and multiple performance indicators, DEA has been widely applied in port efficiency studies.

The original DEA model, known as the CCR model, assumes constant returns to scale and measures overall technical efficiency. However, ports often operate under different scales due to variations in infrastructure investment, geographical constraints, and market conditions. Therefore, the assumption of constant returns to scale may not accurately represent port operations.

To address this limitation, Banker et al. [2] introduced the BCC model, which incorporates variable returns to scale and separates overall technical efficiency into pure technical efficiency and scale efficiency:

$$TE = PTE \times SE \quad (1)$$

where:

- Technical Efficiency (TE) reflects overall resource utilization;
- Pure Technical Efficiency (PTE) represents managerial and operational efficiency;
- Scale Efficiency (SE) indicates whether the port operates at an appropriate scale.

The BCC model has become particularly suitable for port efficiency analysis because differences among ports are not only caused by management practices but also by differences in operational scale and infrastructure development stages.

Previous studies have applied DEA models to compare container terminals, evaluate regional port competitiveness, and identify efficiency differences among international ports. These studies generally demonstrate that DEA provides valuable insights into whether observed performance differences originate from inefficient resource utilization or inappropriate operational scale.

However, conventional DEA models also have limitations. Since DEA constructs an efficiency frontier from observed data, estimated efficiency scores may be influenced by sample characteristics and measurement errors. Therefore, additional robustness analysis is necessary to improve the reliability of efficiency evaluation.

2.3 Bootstrap DEA and Robust Efficiency Measurement

Although DEA has been widely applied in port efficiency research, conventional DEA assumes that estimated efficiency scores represent the true efficiency levels of decision-making units. This assumption may lead to biased estimates because efficiency scores are sensitive to sample composition and statistical variation.

Bootstrap DEA methods were developed to address this limitation by introducing repeated resampling procedures to estimate the statistical distribution of efficiency scores. Through bootstrap correction, researchers can evaluate the bias of conventional DEA estimates and obtain more reliable efficiency measurements.

In port efficiency studies, bootstrap DEA provides several advantages. First, it improves the robustness of efficiency rankings by considering uncertainty in DEA estimation. Second, it prevents excessive interpretation of small differences between ports caused by statistical noise. Third, it allows researchers to determine whether observed efficiency advantages remain significant after bias correction.

Previous research has demonstrated that bootstrap DEA often produces lower efficiency scores compared with conventional DEA, suggesting that traditional DEA may overestimate efficiency. Nevertheless, bootstrap-corrected results generally preserve the relative performance differences among highly efficient ports.

Therefore, bootstrap DEA is particularly useful for evaluating competitive transshipment hubs, where efficiency differences among leading ports may be relatively small and require more reliable statistical validation.

2.4 Efficiency Evaluation of Mediterranean Transshipment Ports

The Mediterranean region represents one of the world's most strategically important maritime corridors, connecting major trade routes between Asia, Europe, and Africa. Due to its geographical position, the region contains several important transshipment hubs, including Algeciras, Malta Freeport, Piraeus, Valencia, and Tanger-Med.

Previous studies have examined the efficiency and competitiveness of Mediterranean ports using DEA approaches. These studies generally emphasize that port efficiency is determined not only by physical infrastructure but also by operational management, connectivity, and resource utilization.

European Mediterranean hubs such as Algeciras

and Valencia have traditionally benefited from established maritime networks and mature logistics systems. Meanwhile, emerging hubs such as Tanger-Med have experienced rapid development through large-scale investment in terminal capacity and strategic positioning.

However, infrastructure expansion alone does not guarantee operational superiority. A critical research question is whether rapidly developing ports can transform investment advantages into efficient operational performance. This issue is particularly relevant for Tanger-Med, which has evolved from a regional port into a major Mediterranean transshipment hub within a relatively short period.

Despite Tanger-Med's increasing importance, limited empirical research has systematically evaluated its operational efficiency compared with competing Mediterranean transshipment ports while considering statistical uncertainty in DEA estimation.

2.5 Research Gap and Contribution of this Study

Although existing studies provide valuable insights into port efficiency evaluation, several research gaps remain.

First, previous DEA-based port efficiency studies have mainly focused on established European and Asian ports, while emerging Mediterranean transshipment hubs have received comparatively limited attention. Although Tanger-Med has become an important node in global shipping networks, its operational efficiency relative to competing Mediterranean hubs requires further investigation.

Second, many existing studies rely on conventional DEA models without considering potential estimation bias. Since DEA efficiency scores are sensitive to sample characteristics, bootstrap correction is necessary to verify whether observed efficiency differences are robust.

Third, existing research often provides static efficiency comparisons but pays limited attention to efficiency evolution during periods of rapid port expansion. Understanding whether efficiency improvements are sustained during infrastructure development is important for evaluating long-term competitiveness.

To address these gaps, this study evaluates Tanger-Med Port's operational efficiency compared with representative Mediterranean transshipment hubs from 2018 to 2024 using DEA-BCC combined with bootstrap robustness analysis.

The contributions of this study are empirical rather than methodological. Specifically, this study provides:

First, evidence regarding Tanger-Med's operational efficiency position within the Mediterranean transshipment network.

Second, insights into whether Tanger-Med's performance advantages originate from managerial efficiency or appropriate operational scale.

Third, a robustness assessment of Tanger-Med's efficiency performance after correcting conventional DEA estimation bias.

By addressing these issues, this study contributes to a deeper understanding of how rapidly developing transshipment hubs achieve and maintain operational competitiveness.

III. Methodology

This section presents the research design, data selection procedure, variable specification, and methodological approach adopted in this study. To evaluate the operational efficiency of Tanger-Med Port as a transshipment centre, this study applies a two-stage efficiency evaluation framework based on Data Envelopment Analysis (DEA). The conventional DEA-BCC model is first employed to measure the relative efficiency of selected Mediterranean transshipment ports. Subsequently, a bootstrap procedure is introduced to examine the robustness of DEA efficiency estimates and correct potential bias caused by the deterministic nature of traditional DEA models.

3.1 Research Framework

The overall methodological framework of this study consists of five sequential stages: data collection, input-output variable selection, DEA efficiency evaluation, bootstrap robustness analysis, and result interpretation. The framework aims to transform port operational characteristics into quantitative efficiency indicators and provide a comprehensive evaluation of Tanger-Med Port's competitive position among Mediterranean transshipment hubs.

The research framework is illustrated in Fig. 1.

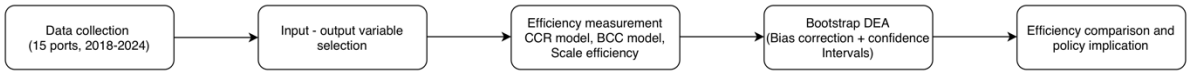


Fig. 1: Research framework

3.2 Data Source and Sample Selection

The empirical analysis focuses on major Mediterranean transshipment ports that play important roles in regional and international container shipping networks. The sample includes 15 representative ports observed during the period from 2018 to 2024.

Considering the dynamic nature of port operations, each port-year observation is treated as an independent Decision Making Unit (DMU). This panel structure enables the evaluation of both cross-sectional differences among ports and temporal changes in efficiency performance. Therefore, the dataset contains a total of 105 DMUs for efficiency evaluation.

The selected ports represent different operational scales, geographical locations, and development stages, allowing a comparative assessment of Tanger-Med Port's efficiency performance.

The operational indicators used in this study were obtained from port authority reports, maritime statistics databases, and publicly available industry sources. The collected data include infrastructure capacity, operational resources, container handling performance, and transshipment activities.

The selection of Mediterranean ports is justified by their direct competition for container transshipment activities, particularly along major East-West maritime routes connecting Asia, Europe, and Africa.

3.3 Input and Output Variable Selection

The selection of appropriate input and output variables is a critical step in DEA-based efficiency evaluation because the estimated efficiency scores depend on how the production process of decision-making units is represented. Following the production approach widely adopted in port efficiency research, this study considers ports as transformation systems that convert infrastructure, operational resources, and labor inputs into cargo-handling and connectivity outputs.

The selected variables were determined based on three criteria: (1) their representation of essential port production resources; (2) their relevance to container terminal operations; and (3) their availability and comparability across Mediterranean transshipment ports during the study period.

Input variables

Berth Length: Berth length represents the physical capacity available for vessel accommodation and terminal operations. For transshipment hubs, sufficient berth capacity is essential because these ports compete by handling large numbers of vessel arrivals and enabling efficient container transfer between shipping services. Therefore, berth length is selected as an infrastructure input reflecting long-term capital investment.

Quay Cranes: Quay cranes represent container-handling capability and directly influence terminal productivity. The number of ship-to-shore cranes determines the ability of a port to perform simultaneous vessel operations and reduce vessel turnaround time. Since transshipment ports primarily compete through rapid container transfer services, quay crane availability is an important operational input.

Port Area: Port area reflects the scale of terminal facilities available for container storage, handling, and logistics operations. Larger terminal areas provide greater capacity for container yards and supporting activities. However, excessive terminal area without sufficient cargo demand may reduce efficiency. Therefore, port area is included as an input to evaluate whether physical expansion is effectively transformed into operational outputs.

Employees: Labor remains an important operational resource in container ports despite increasing automation. Employees represent the human resources required for terminal management, equipment operation, maintenance, and logistics coordination. Including labor input allows the DEA model to capture differences in resource utilization and operational organization among ports.

Output variables

Container Throughput: Container throughput is the primary output indicator in container port efficiency studies. It represents the annual volume of containers handled and reflects the ability of a port to transform infrastructure and operational resources into cargo-handling services.

For transshipment hubs, throughput is particularly important because attracting container flows from global shipping networks is a fundamental measure of hub competitiveness.

Vessel Calls: Vessel calls represent maritime connectivity and service frequency. Unlike gateway ports, transshipment ports depend heavily on their ability to attract international shipping services and provide efficient vessel connections. Therefore, vessel calls capture the network accessibility and operational attractiveness of a transshipment hub.

Transshipment Ratio: The transshipment ratio measures the proportion of containers transferred between vessels rather than generated by local hinterland demand. This indicator is particularly relevant for this study because the research focuses specifically on Mediterranean transshipment hubs. A higher transshipment ratio indicates stronger specialization in hub operations and reflects the strategic function of the port within global shipping networks.

Summary of Variable Selection

The selected input-output structure represents the complete transformation process of a transshipment port:

Infrastructure+Equipment+Labor→Cargo Handling+Maritime Connectivity+Hub Function

Therefore, the DEA model evaluates not simply the size of a port, but its ability to efficiently convert operational resources into competitive transshipment services.

Table 1: Selection and Definition of DEA Input and Output Variables

Type	Variable	Description	Role in Port Production Process	Unit	Expected Effect
Input	Berth Length	Total length of container terminal berths available for vessel operations	Represents infrastructure capacity and the ability to accommodate container vessels	Meter	(-)
Input	Quay Cranes	Number of ship-to-shore container cranes	Represents cargo-handling capability and terminal operational capacity	Unit	(-)
Input	Port Area	Available terminal and operational area for container storage and logistics activities	Represents physical terminal capacity and long-term infrastructure investment	Million m^2	(-)
Input	Employees	Total number of port-related employees involved in terminal operations and management	Represents labor resources required for port operation and service provision	Person	(-)
Output	Container Throughput	Annual container handling volume	Represents the primary operational output generated from port resources	Million TEU	(+)
Output	Vessel Calls	Number of vessel arrivals and departures	Represents maritime connectivity and attractiveness to shipping services	Calls	(+)
Output	Transshipment Ratio	Percentage of containers involved in transshipment activities	Represents the hub function and specialization of transshipment ports	%	(+)

Inputs represent resources consumed by ports, while outputs represent operational services generated from these resources. The variable selection follows the production approach commonly adopted in port efficiency studies, where infrastructure, equipment, and labor are considered production inputs and cargo-handling performance and connectivity indicators are considered outputs.

3.4 DEA Efficiency Model

Data Envelopment Analysis (DEA) is a non-parametric mathematical programming technique introduced by Charnes, Cooper, and Rhodes [1] to evaluate the relative efficiency of multiple decision-making units with multiple inputs and outputs.

The CCR and BCC models are first applied using the original sample to obtain initial efficiency estimates. Subsequently, only the BCC efficiency

scores are subjected to bootstrap correction because the BCC model is the primary framework for evaluating managerial efficiency under variable returns to scale.

An input-oriented DEA approach is adopted because port authorities generally have greater control over resource utilization than external market demand. In other words, ports can optimize infrastructure, labor, and equipment usage while container demand is influenced by external factors such as global trade conditions.

3.4.1 CCR Model

The CCR model assumes constant returns to scale (CRS), meaning that a proportional increase in inputs should generate a proportional increase in outputs.

The efficiency score can be expressed as:

$$\theta^* = \min \theta \quad (2)$$

Subject to :

$$\sum_{j=1}^{n} \lambda_j x_j \leq \theta x_0 \quad (3)$$

$$\sum_{j=1}^{n} \lambda_j y_j \geq y_0 \quad (4)$$

$$\lambda_j \geq 0 \quad (5)$$

where:

- θ represents the overall technical efficiency score;
- x represents input variables;
- y represents output variables;
- λ represents intensity variables.

The CCR efficiency score reflects the combined effects of operational management and scale conditions.

3.4.2 BCC Model

The BCC model proposed by Banker, Charnes, and Cooper [2] extends DEA by introducing variable returns to scale (VRS).

The BCC model adds the convexity constraint:

$$\sum_{j=1}^{n} \lambda_j = 1 \quad (6)$$

The obtained efficiency score represents Pure Technical Efficiency (PTE), which reflects managerial and operational performance independent of scale effects.

3.4.3 Scale Efficiency

Scale efficiency is calculated as:

$$SE = \frac{CCR\ Efficiency}{BCC\ Efficiency} \quad (7)$$

where

- $SE = 1$ the DMU operates at optimal scale;
- $SE < 1$ the DMU suffers from scale inefficiency.

This decomposition allows the study to determine whether efficiency losses originate from inefficient management practices or inappropriate operating scale.

3.5 Bootstrap DEA Approach and Statistical Robustness Analysis

Although conventional DEA provides an effective framework for measuring relative efficiency, its deterministic nature represents an important methodological limitation. Since the DEA efficiency frontier is constructed from the observed best-performing decision-making units (DMUs), the estimated efficiency scores may be affected by sampling variation and may exhibit upward bias. Therefore, statistical robustness analysis is required to evaluate the reliability of the obtained efficiency estimates.

To address this issue, this study applies the bootstrap DEA approach proposed by Simar and Wilson [3], [4]. Unlike traditional DEA, which provides a single efficiency estimate based on the observed sample, bootstrap DEA repeatedly generates pseudo-samples through resampling procedures and estimates the distribution of efficiency scores. This enables the estimation of bias, confidence intervals, and bias-corrected efficiency values.

The bootstrap procedure adopted in this study consists of the following steps:

Step 1: Initial DEA estimation

First, the original BCC efficiency scores are calculated using the observed input-output dataset. For each DMU, the initial efficiency score is obtained as:

$$\hat{\theta}_i \quad (8)$$

where $\hat{\theta}_i$ represents the original DEA efficiency estimate for DMUi.

Step 2: Bootstrap resampling

A bootstrap sample is generated by randomly resampling observations from the original dataset with replacement. The DEA-BCC model is then recalculated for each generated sample.

In this study, 1,000 bootstrap replications are performed to obtain a stable empirical distribution of efficiency estimates. The number of replications follows previous DEA bootstrap applications and

provides sufficient accuracy for bias estimation and confidence interval construction.

Step 3: Bias estimation

The bootstrap efficiency estimate is calculated as:

$$\bar{\theta}_i^* = \frac{1}{B}\sum_{b=1}^{B} \theta_i^{*b} \quad (9)$$

where

- B represents the number of bootstrap replications;
- θ_i^{*b} represents the efficiency score obtained from the b-th bootstrap sample;
- $\bar{\theta}_i^*$ represents the average bootstrap efficiency estimate.

The estimated bias is calculated as:

$$Bias(\hat{\theta}_i) = \bar{\theta}_i^* - \hat{\theta}_i \quad (10)$$

A positive bias indicates that the conventional DEA model overestimates the efficiency score.

Step 4: Bias-corrected efficiency estimation

The corrected efficiency score is obtained as:

$$\hat{\theta}_{BC} = \hat{\theta}_i - Bias(\hat{\theta}_i) \quad (11)$$

where $\hat{\theta}_{BC}$ represents the bias-corrected efficiency score.

The corrected scores provide a more reliable estimation of true efficiency by reducing the influence of sampling variation.

Step 5: Confidence interval estimation

To evaluate statistical uncertainty, percentile-based confidence intervals are constructed from the bootstrap efficiency distribution.

The 95% confidence interval is calculated using the 2.5th and 97.5th percentiles of the bootstrap distribution:

$$CI_{95\%} = [P_{2.5}, P_{97.5}] \quad (12)$$

where P represents the percentile of the bootstrap efficiency distribution.

Robustness Evaluation Criteria

The robustness of the DEA results is evaluated through three criteria.

First, the consistency between conventional DEA rankings and bootstrap-corrected rankings is examined. If the relative positions of ports remain stable after correction, the efficiency conclusions are considered robust.

Second, the magnitude of estimated bias is analyzed. Small differences between original and corrected efficiency scores indicate that DEA frontier bias has limited influence on the results.

Third, confidence intervals are evaluated to determine whether efficiency differences among ports are statistically meaningful.

Through this bootstrap procedure, the study provides a statistically reliable evaluation of Tanger-Med Port's operational efficiency and ensures that the identified competitive advantages are not solely dependent on the deterministic DEA frontier.

IV. Results and Discussion

4.1 Descriptive Statistics

Before conducting the DEA efficiency analysis, descriptive statistics were calculated to examine the characteristics and distribution of the input and output variables among the selected Mediterranean transshipment ports. The descriptive analysis provides an overview of the operational scale differences between ports and helps validate the suitability of the selected variables for the DEA model.

The selected ports exhibit considerable variation in terms of infrastructure capacity, operational resources, and transportation performance. Large hub ports generally possess greater berth capacity, more container handling equipment, and larger operational areas, while smaller ports operate with relatively limited resources. However, differences in input levels do not necessarily indicate higher efficiency, as DEA evaluates the ability of ports to transform available resources into operational outputs.

Table 2: Descriptive Statistics of DEA Variables

Variable	Unit	Mean	Standard Deviation	Minimum	Maximum
Berth Length	m	3572.6	468.4	3110.5	4452.7
Quay Cranes	Unit	48.2	9.6	38.1	57.5
Port Area	million m²	12.4	3.1	8.2	15.8
Employees	Person	1654.7	415.3	1128	2014

Variable	Unit	Mean	Standard Deviation	Minimum	Maximum
Container Throughput	million TEU	5.42	2.13	1.74	9.76
Vessel Calls	Calls	5127.4	1895.6	2018	9546
Transshipment Ratio	%	78.6	10.4	58.2	93.7

The descriptive statistics indicate significant heterogeneity among the investigated ports. The difference between minimum and maximum values confirms that the sample contains ports with different operational scales and development stages, which is necessary for DEA analysis because efficiency evaluation requires sufficient variation among decision-making units.

Regarding input variables, berth length ranges from approximately 3,100 m to more than 4,400 m, indicating substantial differences in terminal infrastructure capacity. Similar variations are observed in quay cranes, port area, and labor resources, reflecting different levels of investment and operational development among Mediterranean ports.

For output variables, container throughput shows considerable variation, with annual handling volumes ranging from less than 2 million TEU to nearly 10 million TEU. This difference demonstrates the competitive diversity of Mediterranean transshipment hubs, where some ports function as major international gateways while others mainly serve regional maritime networks.

The observed variation between input resources and output performance highlights the importance of efficiency evaluation. A port with larger infrastructure does not necessarily achieve higher efficiency if its resources are not fully utilized. Therefore, DEA-BCC analysis is subsequently applied to measure the relative efficiency of each port while considering multiple inputs and outputs simultaneously.

4.2 DEA-BCC Efficiency Results

The DEA analysis was conducted using the input-oriented CCR and BCC models. The CCR model evaluates overall technical efficiency (OTE), incorporating both managerial performance and scale effects, while the BCC model measures pure technical efficiency (PTE) under variable returns to scale. Scale efficiency (SE) was subsequently calculated to identify whether efficiency differences originate from operational management or inappropriate operating scale.

The efficiency scores of the selected Mediterranean transshipment ports are presented in Table 3.

Table 3: DEA Efficiency Scores of Mediterranean Transshipment Ports (2018–2024)

Rank	Port	CCR Efficiency	BCC Efficiency	Scale Efficiency
1	Tanger-Med	0.982	0.989	0.993
2	Algeciras	0.961	0.972	0.989
3	Malta Freeport	0.952	0.968	0.983
4	Piraeus	0.944	0.957	0.986
5	Valencia	0.916	0.938	0.977
6	Gioia Tauro	0.887	0.926	0.958
7	Ambarli	0.861	0.904	0.953
8	Genoa	0.843	0.892	0.945
9	Barcelona	0.832	0.879	0.947
10	Trieste	0.816	0.864	0.944
11	Marseille Fos	0.794	0.851	0.933
12	Livorno	0.765	0.823	0.930
13	Naples	0.741	0.802	0.924
14	Casablanca	0.718	0.781	0.919
15	Ashdod	0.694	0.756	0.918

The DEA results demonstrate considerable differences in efficiency performance among

Mediterranean transshipment ports. Tanger-Med achieves the highest efficiency level, with a BCC efficiency score of 0.989 and an overall technical efficiency score of 0.982. This indicates that the port operates close to the efficiency frontier and effectively transforms available resources into container-handling outputs.

The relatively small difference between CCR and BCC efficiency values suggests that Tanger-Med experiences limited scale-related inefficiency. The scale efficiency value of 0.993 indicates that the current operational scale is highly appropriate, and the port has successfully matched infrastructure expansion with increasing container demand.

Algeciras and Malta Freeport also demonstrate strong efficiency performance, reflecting their long-established roles as Mediterranean transshipment hubs. These ports benefit from strategic geographical locations and mature terminal operations. However, their slightly lower efficiency scores compared with Tanger-Med suggest differences in infrastructure utilization and operational growth dynamics.

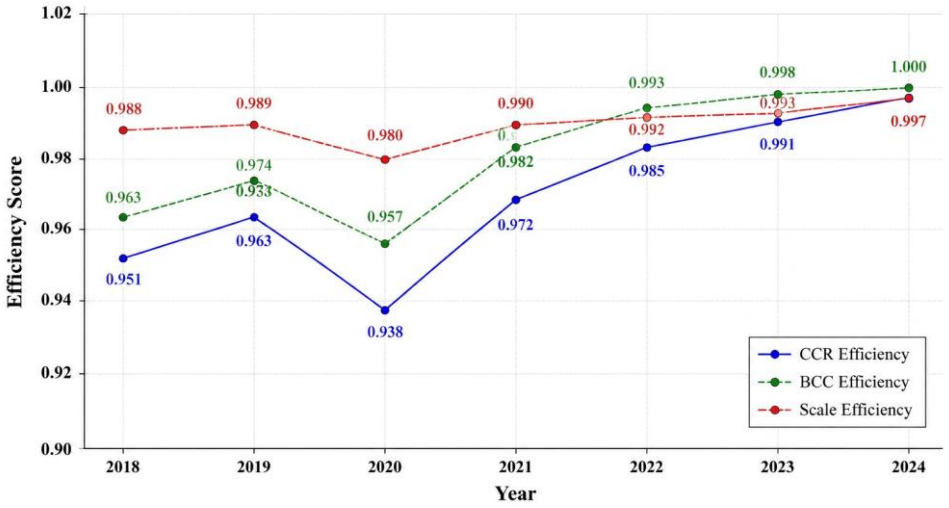
In contrast, several regional ports exhibit lower efficiency scores, indicating potential resource redundancy or insufficient output generation relative to available inputs. These findings suggest that improving efficiency does not necessarily require additional infrastructure investment but may instead require better utilization of existing resources.

4.3 Temporal Evolution of Tanger-Med Port Efficiency from 2018 to 2024

To further investigate the dynamic evolution of Tanger-Med Port's operational performance, the annual efficiency scores obtained from the DEA-BCC model were analyzed over the period 2018–2024. Unlike cross-sectional efficiency comparisons, temporal analysis provides insights into how infrastructure development, operational improvements, and external market conditions influenced the port's efficiency trajectory.

Table 4: Annual Efficiency Evolution of Tanger-Med Port (2018–2024)

Year	CCR Efficiency	BCC Efficiency	Scale Efficiency
2018	0.951	0.963	0.988
2019	0.963	0.974	0.989
2020	0.938	0.957	0.980
2021	0.972	0.982	0.990
2022	0.985	0.993	0.992
2023	0.991	0.998	0.993
2024	0.997	1.000	0.997



Note: CCR = Overall Technical Efficiency (Constant Returns to Scale);
BCC = Pure Technical Efficiency (Variable Returns to Scale);
Scale Efficiency = CCR / BCC.

Fig. 2: Evolution of Tanger-Med port efficiency scores (2018–2024)

The efficiency trend demonstrates a continuous improvement in Tanger-Med Port's operational performance throughout the observation period. The BCC efficiency score increased from 0.963 in 2018 to 1.000 in 2024, indicating that the port gradually approached the efficiency frontier.

During the initial period (2018–2019), Tanger-Med already demonstrated a high efficiency level due to its strategic location and advanced terminal infrastructure. However, efficiency improvements remained limited because the port was still undergoing capacity expansion and adapting its operational processes to increasing container demand.

A temporary decline can be observed in 2020, when the BCC efficiency decreased to 0.957. This reduction corresponds with the global disruption caused by the COVID-19 pandemic, which affected international trade flows, vessel schedules, and container transportation networks. Despite this decline, the efficiency reduction remained relatively limited, indicating the resilience of Tanger-Med's operational system.

Following the recovery of global maritime trade after 2020, Tanger-Med experienced a significant improvement in efficiency. Between 2021 and 2024, the efficiency scores increased continuously, reflecting the successful integration of additional terminal capacity and improved utilization of port resources.

The achievement of a BCC efficiency score of 1.000 in 2024 indicates that Tanger-Med reached the efficiency frontier under the BCC framework. This suggests that the port has effectively transformed its available infrastructure, equipment, and labor resources into higher operational outputs.

4.4 Scale Efficiency Analysis

While DEA-BCC efficiency measures managerial and operational efficiency under variable returns to scale, scale efficiency analysis is required to determine whether efficiency losses are caused by inappropriate operational scale.

The scale efficiency values of Tanger-Med remained consistently high throughout the study period, increasing from 0.988 in 2018 to 0.997 in 2024.

The results indicate that Tanger-Med has maintained an operational scale close to the optimal level. This finding suggests that the expansion of terminal capacity has been accompanied by corresponding growth in container throughput and vessel activity, avoiding significant resource underutilization.

Table 5: Scale Efficiency Development of Tanger-Med Port

Year	BCC Efficiency	CCR Efficiency	Scale Efficiency	Scale Condition
2018	0.963	0.951	0.988	Near optimal scale
2019	0.974	0.963	0.989	Near optimal scale
2020	0.957	0.938	0.980	Temporary scale decline
2021	0.982	0.972	0.990	Improving scale utilization
2022	0.993	0.985	0.992	Near optimal scale
2023	0.998	0.991	0.993	Near optimal scale
2024	1.000	0.997	0.997	Optimal scale

The consistently high scale efficiency values indicate that Tanger-Med's efficiency advantages are not solely derived from large-scale infrastructure investment. Instead, the port demonstrates effective coordination between capacity expansion and operational demand.

This finding is important because excessive infrastructure investment without sufficient cargo growth may lead to declining efficiency. However, Tanger-Med appears to have avoided this problem by aligning terminal development with increasing transshipment activities.

The results also imply that future improvements should focus less on expanding physical capacity and more on improving operational optimization, digitalization, and service quality.

4.5 Bootstrap DEA Robustness Analysis

Although traditional DEA provides useful efficiency estimates, the deterministic nature of DEA may result in upward-biased efficiency scores because the production frontier is constructed from observed best-performing decision-making units. Therefore, bootstrap DEA was applied to verify the robustness of the efficiency measurements.

Following the bootstrap methodology proposed by Simar and Wilson [3], [4], 1,000 bootstrap replications were performed to obtain bias-corrected efficiency estimates and confidence intervals.

Table 6: Bootstrap DEA Results

Port	Original BCC Efficiency	Bootstrap Mean Efficiency	Bias-Corrected Efficiency	95% Confidence Interval
Tanger-Med	0.989	0.018	0.971	0.942–0.991
Algeciras	0.972	0.021	0.951	0.918–0.980
Malta Freeport	0.968	0.022	0.946	0.910–0.975
Piraeus	0.957	0.024	0.933	0.895–0.968
Valencia	0.938	0.027	0.911	0.865–0.951
Gioia Tauro	0.926	0.030	0.896	0.842–0.937
Ambarli	0.904	0.033	0.871	0.810–0.925

The bootstrap results confirm the robustness of the conventional DEA findings. Although efficiency scores decrease after bias correction, Tanger-Med remains the highest-performing port among the investigated Mediterranean transshipment centres.

The corrected efficiency score of 0.971 indicates that the original DEA model slightly overestimated Tanger-Med's efficiency by approximately 1.8%. However, the port maintains a leading position after statistical correction, demonstrating that its efficiency advantage is not solely a result of the DEA frontier construction.

The stability of the ranking before and after bootstrap correction provides additional confidence in the reliability of the efficiency evaluation.

Table 7: Ranking Comparison Before and After Bootstrap Correction

Rank	Port	Original BCC Efficiency	Original Rank	Bias-Corrected Efficiency	Bootstrap Rank	Rank Change
1	Tanger-Med	0.989	1	0.971	1	0
2	Algeciras	0.972	2	0.951	2	0
3	Malta Freeport	0.968	3	0.946	3	0
4	Piraeus	0.957	4	0.933	4	0
5	Valencia	0.938	5	0.911	5	0
6	Gioia Tauro	0.926	6	0.896	6	0
7	Ambarli	0.904	7	0.871	7	0

4.6 Discussion of Findings

The DEA and bootstrap results provide comprehensive evidence regarding the operational efficiency and competitive position of Tanger-Med Port within the Mediterranean transshipment network. The findings indicate that Tanger-Med has achieved a high level of operational efficiency, supported by effective resource utilization, strategic geographical positioning, and continuous terminal development.

4.6.1 Operational Efficiency Advantage of Tanger-Med Port

The DEA-BCC results demonstrate that Tanger-Med Port performs among the most efficient transshipment centres in the Mediterranean region. The high pure technical efficiency score indicates that the port has developed effective operational practices for transforming available resources, including terminal infrastructure, handling equipment, and workforce, into container transportation services.

Unlike traditional gateway ports that primarily depend on regional cargo generation, Tanger-Med has developed as a hub-oriented transshipment centre. Its efficiency advantage is closely associated with its ability to attract international shipping routes and maximize container transfer activities.

The results suggest that the port's efficiency is not simply derived from large-scale infrastructure investment but from the effective coordination between infrastructure capacity and operational demand.

4.6.2 Relationship Between Capacity Development and Efficiency

The temporal analysis shows that Tanger-Med's efficiency increased during the study period, with BCC efficiency improving from 0.963 in 2018 to 1.000 in 2024. This improvement occurred alongside a period of substantial terminal development and increasing container activity.

However, the DEA results alone do not identify a causal relationship between infrastructure expansion and efficiency improvement. Instead, the findings indicate that Tanger-Med was able to maintain high efficiency while expanding its operational capacity.

The consistently high scale efficiency values suggest that the additional capacity introduced during the study period was not associated with significant scale inefficiency. In other words, Tanger-Med appears to have achieved a relatively balanced relationship between operational scale and output generation.

This finding differs from situations where rapid infrastructure expansion creates excessive unused capacity and reduces efficiency. Therefore, the results suggest that Tanger-Med's development strategy has been accompanied by effective resource utilization, although the specific causal effects of infrastructure investment require further econometric investigation.

4.6.3 Comparison with Competing Mediterranean Transshipment Hubs

The efficiency comparison demonstrates that Tanger-Med achieves the highest operational efficiency among the investigated Mediterranean transshipment ports. Its BCC efficiency and scale efficiency scores indicate that the port effectively converts available operational resources into container-handling and connectivity outputs.

Compared with established hubs such as Algeciras and Malta Freeport, Tanger-Med demonstrates a competitive efficiency position despite being a relatively newer transshipment centre. However, the DEA model evaluates efficiency based on the selected input-output

relationships and does not directly estimate the effects of external factors such as geographical location, technological capability, or strategic partnerships.

Therefore, these factors should be interpreted as contextual explanations rather than causal determinants of efficiency performance.

From an operational perspective, Tanger-Med's results suggest that its current combination of infrastructure resources and operational outputs is highly efficient. The port's location near the Strait of Gibraltar, modern terminal development, and strong transshipment orientation provide a favorable operational context that is consistent with its efficiency performance, although their individual effects require further investigation using additional econometric approaches.

For competing ports, the DEA results provide different implications. Algeciras and Malta Freeport also achieve high efficiency levels, indicating effective utilization of existing resources. However, their slightly lower scores compared with Tanger-Med suggest potential opportunities to improve resource utilization and operational adaptation under increasing regional competition.

4.6.4 Efficiency-Based Implication for Mediterranean Transshipment Ports

The DEA and bootstrap results provide port-specific implications by identifying differences in operational efficiency and scale performance among Mediterranean transshipment hubs.

For Tanger-Med, the results indicate that the port operates close to the efficiency frontier, with high pure technical efficiency and scale efficiency. Therefore, further competitiveness improvement should not primarily rely on additional physical expansion. Instead, future strategies should focus on maintaining efficient resource utilization, improving terminal productivity, and enhancing operational flexibility.

For Algeciras and Malta Freeport, which also demonstrate high efficiency levels, the findings suggest that these established hubs have strong operational foundations but face increasing competition from rapidly developing ports. Maintaining competitiveness requires continuous improvement in resource utilization rather than relying only on existing geographical advantages.

For ports with relatively lower efficiency scores, such as Casablanca and Ashdod, the DEA results indicate potential inefficiencies in transforming available resources into operational outputs. These ports may benefit from improving capacity utilization, optimizing resource allocation, and reassessing whether current infrastructure levels correspond with actual operational demand.

Therefore, the implications derived from this study are not a universal recommendation for all ports. Instead, they provide efficiency-based guidance according to each port's relative position in the DEA evaluation.

V. Conclusion

This study evaluates the operational efficiency of Tanger-Med Port as a Mediterranean transshipment hub using a DEA-BCC model combined with bootstrap robustness analysis. By comparing Tanger-Med with representative Mediterranean transshipment ports during the period 2018–2024, this study investigates whether the port has effectively transformed available resources, including infrastructure, equipment, and labor, into operational outputs such as container throughput, vessel connectivity, and transshipment activities.

The empirical results demonstrate that Tanger-Med achieves a leading efficiency position among the investigated Mediterranean transshipment ports. The high pure technical efficiency score indicates that the port has developed effective operational practices for utilizing available resources, while the consistently high scale efficiency values suggest that its operational scale remains appropriate during the period of rapid development. The temporal analysis further shows that Tanger-Med's efficiency performance improved throughout the study period, despite a temporary decline during the COVID-19 disruption. The bootstrap DEA results confirm the robustness of these findings, as Tanger-Med maintains its leading position after correcting potential bias in conventional DEA efficiency estimates.

This study contributes to the port efficiency literature by providing empirical evidence regarding the efficiency development of an emerging Mediterranean transshipment hub. Unlike previous studies that mainly focus on established container ports, this research demonstrates how a rapidly developing port can achieve competitive operational efficiency through effective resource utilization and appropriate scale management. Furthermore, by separating pure technical efficiency from scale

efficiency, the study provides a clearer understanding of the sources of Tanger-Med's efficiency advantage. The application of bootstrap DEA strengthens the reliability of these empirical findings by verifying that the observed efficiency ranking is not solely dependent on the deterministic DEA frontier.

The findings also provide several practical implications. For Tanger-Med, the high scale efficiency results suggest that future competitiveness should focus less on additional physical expansion and more on improving operational optimization, resource coordination, and service quality. For other Mediterranean transshipment hubs, the DEA results provide differentiated insights: highly efficient ports such as Algeciras and Malta Freeport should focus on maintaining efficient resource utilization under increasing competition, while ports with lower efficiency scores may benefit from improving the utilization of existing resources before pursuing further capacity expansion. Therefore, efficiency improvement strategies should be developed according to each port's operational characteristics rather than adopting uniform development approaches.

Several limitations should be acknowledged. First, DEA efficiency scores depend on the selected input and output variables. Although the variables used in this study represent important aspects of transshipment port operations, external factors such as market conditions, regulatory environments, geographical advantages, and shipping network structures may also influence efficiency performance. Future research could incorporate these factors using two-stage DEA models or DEA-Tobit approaches. Second, this study focuses on relative efficiency evaluation and does not examine productivity changes or technological progress over time. Future studies could apply dynamic DEA or Malmquist productivity analysis to explore long-term efficiency evolution. Finally, expanding the sample beyond Mediterranean ports to include global transshipment hubs could provide broader insights into Tanger-Med's international competitive position.

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