LOGISTICS EFFICIENCY ANALYSIS OF MEDITERRANEAN CONTAINER TERMINALS: A DEA AND SFA COMPARISON OF PORT SAID EAST, TANGIER MED AND PIRAEUS

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ABSTRACT: This research investigates the operational efficacy of Mediterranean container terminals. This research examines the obstacles to regional competitiveness encountered by Port Said East (Egypt), Tangier Med (Morocco), and Piraeus (Greece), which are attributable to the Red Sea crisis and concurrent transformations in global supply chains. This research assesses the operational efficacy of three Mediterranean container terminals Port Said East, Tangier Med, and Piraeus to examine regional competitiveness challenges in the context of the Red Sea crisis and evolving supply chain dynamics. Building upon the work of Cullinane et al. (2006), this research employs frontier methodologies to detect performance deficiencies, with a particular focus on infrastructure and digitization to improve globalization and logistics performance rankings. A quantitative case research methodology was adopted, incorporating Data Envelopment Analysis (DEA) utilizing CCR and BCC models, in conjunction with Stochastic Frontier Analysis (SFA). Cross-sectional data pertaining to the year 2024 were obtained from port authorities and World Bank reports, evaluating variables such as quay length, crane capacity, and terminal area in relation to TEU throughput. Hypotheses validated the positive effect of infrastructure on productivity. Following a $500 million expansion, Port Said East achieved full operational efficiency (CCR: 1.0, BCC: 1.0) in 2024, processing 4.44 million TEU. It is ranked as the third-best port globally according to CPPI. Tangier Med achieved a score of 1.0 in both models, with a total of 10.24 million TEU across the complex, ranking fifth. Piraeus exhibited operational inefficiencies (CCR: 0.78, BCC: 0.85) attributable to scalability challenges, processing 4.79 million TEUs. This research introduces an innovative post-crisis DEA/SFA approach applied to Mediterranean ports, incorporating sustainability considerations. Limitations encompass dependence on secondary data and a cross-sectional design, which may potentially overlook dynamic processes. The research encourage private sector collaborations and the adoption of automation to enhance operational efficiency. In addition, it Promotes employment generation and decrease emissions to support regional stability.

1. INTRODUCTION

The Mediterranean Sea serves as a critical nexus for global trade, linking Europe, Africa and Asia, and in 2025, the volume of cargo crossing this sea exceeded 200 million TEUs, according to UNCTAD (2025). However, since the protracted Red Sea crisis in 2023, geopolitical tensions have caused disruption in the shipping routes (El-Nakib, 2025). The increase in transit times, by 10 to 15 days, and the surge in costs, by 20 to 30%, have severely congested the ports in the Western Mediterranean and

put into sharp focus the need for efficiency increases for them to stay competitive in the face of the powerful ports in Northern Europe, such as Rotterdam.

The World Bank's Container Port Performance Index (CPPI), in its 2024 edition, as made public in September 2025, highlights the striking differences in efficiency, with East Asian ports leading the charge with superior automation and the Mediterranean ports showing a jarring performance. This paper borrows the frontier efficiency framework presented by Cullinane et al. (2006), combining Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) to analyses three key ports in the region, namely Port Said East in Egypt, Tangier Med in Morocco, and Piraeus in Greece. The approach allows us to quantify the technical and scale efficiencies, reveal the areas of brilliance and address the shortcomings. Efficiency at container terminals is basically the backbone of the future of global trade, which is predicted to grow at 3-4% annually until 2030 (UNCTAD, 2025). It is all about streamlining the flow, the use of resources and the sustainability in the face of setbacks, like the aftermath of the pandemic and the Ukraine conflict. However, the 9% share of the world's containers that Mediterranean ports handle are pitted against their inadequate infrastructure, outdated technology and digital slowness, and the average turnaround times went up 9% in 2025, according to Clarkson Research (2025).

The CPPI (2024) lays bare the disparities; Port Said East took the 3rd spot globally with a score of 32 moves per crane-hour, Tangier Med came in at number five, and Piraeus trailed in at 82nd, showing that it has a problem with economies of scale. Looking at the northern end of the Suez Canal, the Alexandria container terminal plays a significant role in Asia-Europe transshipment. The $500 million expansion supported by IFC (2025), which consisted of 955 meters of quay and 510,000 square meters of yard, bumped up its capacity to 7 million TEUs. Coming hustling over into 2024, the terminal handled 4.44 million TEUs, up 4.4% from 2023, and with some 2025 figures showing it was still motoring along despite problems with the canal. Boasting 1,500 jobs, the terminal is also contributing to Egypt's Vision 2030 but, as we saw with the 2021 Ever Given incident, is vulnerable to blockages (UNCTAD, 2025 and World Bank, 2025). Tangier Med, located in Gibraltar, has become the top hub in Africa, and in 2024, it processed 10.24 million TEUs across the whole complex, marking a massive 18.8% jump and exceeding its 9 million TEU capacity following some nifty optimizations. The first six months of 2025 saw a 79-million-ton increase in cargo, and predictions are for an 11 to 12 million TEU load for the year. Its revenues went through the roof last year at $1.212 billion and served 180 ports, creating 130,000 jobs. The Tangier Med's impressive use of automation, including seventy automated rail-mounted cranes, gives it a CPPI score of 135.8, but running into issues with rerouting through the Red Sea has put a strain on its operations. Piraeus, under COSCO since 2009, has also made significant investments. Estimating to handle 4.79 million TEUs in 2025, up from 4.22 million last year (ALM Intelligence, 2025), saw a 32% rise to 546,526 TEUs. At 7.5 to 8.3 million TEUs, its capacity has given it a revenue stream of €230.9 million in 2024 (China Economic Net, 2025), but it has problems with rail integration and EU regulations. Requiring a 30% reduction in emissions by 2030 is hampering its progress (UNCTAD, 2025 and World Bank, 2025).

Well-known objectives of this research are to apply DEA (CCR/BCC) and SFA to 2024-2025 data, testing whether investments in infrastructure can be directly related to productivity. This time, the analysis highlights the strength of location and automation and improvements in digitalization and will go towards guiding policies for the Union for the Mediterranean.

2. LITERATURE REVIEW

2.1 Foundations of Efficiency Measurement in Production Theory

Production theory serves as the theoretical basis, with firms looking to transform inputs into outputs in the best possible way, given the constraints of technology and available resources, when evaluating the efficiency of container terminals. Martínez-Moya et al., (2024) and Gu et al., (2025) stated that efficiency frontiers broke down the concept of efficiency between technical efficiency and allocative efficiency, and that's the basis for much of the work in container terminal efficiency. There are methods in the world of port economics since the 1990s have been Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) as stated by Martínez-Moya et al., (2024) and Efecan (2023) which basically allowed us to empirically compare the efficiency of different ports and identify areas for improvement. Compared to traditional ratio analyses, these methods consider the multiple inputs and outputs of container terminals. A meta-analysis conducted by Schøyen and Odeck (2013) looked at the Mean Technical Efficiency (MTE) scores of 40 studies in the area and discovered that the chosen methods, such as DEA or SFA, affect the results of the analyses, with DEA delivering lower efficiency scores because it is a deterministic method.

When analyzing the performance of decision-making units such as ports, DEA, a non-parametric linear programming technique, is used to draw a boundary of efficient points and classifies these units as either efficient if they fall on the line or inefficient if they don't. Coming from Charnes et al. (1978), the Charnes-Cooper-Rhodes model is a popular DEA variant that considers constant returns to scale and global efficiency. Building off the work of Banker et al. (1984) and Efecan, (2023), the Banker-Charnes-Cooper model allowed for variable returns to scale, differentiating between pure technical efficiency and scale efficiency, and was an important development in the field. Output-orientated DEA is the aim of expanding outputs from a fixed amount of input, which is precisely what ports seek to do, increasing throughput without proportionally increasing inputs, and examples of DEA in the port industry can be seen in Tongzon's (2001) analysis of 16 international ports, which revealed a positive correlation between crane numbers, quay length, and efficiency. Further research, such as Cullinane et al. (2005), showed that private ownership gives a boost to efficiency and kickstart investment and competition.

In addition, SFA is a parametric econometric approach that cuts through the noise in the data by using a stochastic production frontier when analyzing the efficiency of ports. Originating from Aigner et al. (1977), this model dissects the frontier as $\ln Y = \beta_0 + \Sigma \beta_i \ln X_i + v$. U represents the non-negativity of inefficiency, which is basically half-normal, while v represents statistical noise that comes from a perfectly normal distribution. This division of noise and inefficiency is what makes SFA so robust for real-world use, where measurement errors are a common problem. In port studies, Cullinane and Song (2003) and Gu et al., (2025) implemented SFA in UK container terminals, demonstrating that economies of scale and managerial strategies drive efficiency. Lin and Tseng (2005) integrated DEA and SFA to assess the operational efficiency of 27 international container ports, demonstrating that SFA provides insights into potential cost savings, while DEA identifies areas for resource reduction. Serebrisky et al. (2016) took the idea to Latin American ports and used panel SFA to see how the efficiency of these ports changed over time.

Researchers have used two main methods, DEA and SFA, when analyzing the efficiency of global container ports. Cullinane et al. (2006) found a high rank correlation between the two methods, with DEA being more stringent and basically not forgiving any errors in the data. They found that SFA is great for testing hypotheses about what causes inefficiency and in many cases is preferred over DEA (Gu et al., 2025). There are recent developments in this field have led to the creation of hybrid models,

one example of which is Nguyen et al. (2016), who combined DEA with Tobit regression for a second-stage analysis of Vietnamese ports and showed that efficiency was related to hinterland connectivity.

2.2 Applications for Container Port Efficiency

When discussing the efficiency of container ports, the size of the port, its infrastructure, the quality of its equipment and the way it operates are all critical. Barros (2003) in Portugal studied this by applying the DEA method and found that ports that are privatized tend to be rated highly. Going global, Wang and Cullinane (2006) surveyed 104 terminals, noting that the larger the port, the higher the economies of scale. Environmental considerations are also a major factor, with Chang and Tovar's 2014 Spanish ports DEA research extending this to account for undesirable outputs, or carbon emissions. Lu et al. (2023) went further, breaking down sustainable efficiency in ports into two parts. The quay and the yard stage were highlighted where the main bottlenecks occur.

Studies on efficiency show that the Mediterranean, which handles 20% of Europe's container traffic but faces competition from Asian hubs, has geographic advantages and needs more investment. Notteboom (2022) documented connectivity improvements, with the Liner Shipping Connectivity Index rising 15% from 2015 to 2020, yet inefficiencies persist due to fragmented governance. Esmer et al. (2013) benchmarked Mediterranean hubs using DEA, finding Tangier Med efficient owing to automation and strategic positioning. A 2023 research by Schøyen et al. analyzed 35 Mediterranean ports via DEA, identifying that transshipment-focused terminals like Tangier Med outperform gateways in technical efficiency, averaging 0.78 under VRS. Sdoukopoulos and Boile (2021) evaluated ports using DEA, emphasizing key success factors like hinterland access and digitalization, with Piraeus benefiting from COSCO investments but lagging in sustainability metrics.

Recent work by Morales-Fusco et al. (2024) compared transshipment and gateway ports, concluding that hubs like Port Said East achieve higher scores (0.85-1.0) due to economies of scale from mega-vessel handling. Ghiara and Tei (2021) incorporated revenue and tonnage in outputs for Mediterranean ports, finding average efficiency of 0.68 under CRS, suggesting a potential 47% output increase without input expansion. Sustainability integration is increasingly vital, as ports face EU Green Deal mandates for net-zero emissions by 2050. Tichavska and Tovar (2015) used undesirable DEA for air pollutants in Iberian ports, revealing efficiency penalties for high-emission operations. In the Mediterranean, Boile et al. (2023) applied eco-DEA, noting that ports like Tangier Med, with LNG bunkering, score 15% higher in green efficiency.

Theoretical gaps include limited small-sample applications and dynamic analyses incorporating disruptions like the Red Sea crisis. Most studies use cross-sectional data, overlooking time-varying factors; panel SFA addresses this partially (Serebrisky et al., 2016). Mediterranean-specific research often focuses on Western basins, neglecting Eastern dynamics (e.g., Suez impacts). This research bridges these by applying DEA/SFA to three ports, using recent data to test infrastructure-productivity hypotheses, and contributing to policy for regional resilience.

3. METHODOLOGY

3.1 Research Design

The positivist approach took a deep dive into the way these terminals operate, much like case research. When researching the efficiency of container terminals in the Mediterranean region, this research went with a traditional approach. Coming from the work of Cullinane et al. (2006), the design

combines theoretical principles with real-world data to measure the performance of the Port Said East, Tangier Med and Piraeus container terminals, and with its ability to look at every aspect of their operations, it allows for direct observations and confirmation of the results through multiple sources, as per Yin (2014) guidelines. Well-known in the field of evaluating port throughput is the method that was used here, which considers the infrastructure, machinery and equipment of the terminals and translates these into the number of containers being moved from ships to land. The empirical data was also influenced by earlier DEA and SFA studies, as seen in Lin and Tseng's (2005) work, and made use of panel data to strengthen the results.

3.2 Research Approach

Our research relies on a mixed-methods, quantitative approach that is based on the efficiency frontier, which in turn is derived from frontier analysis, when investigating the efficiency of container terminals. According to Creswell (2013), such a numerical approach is well-suited for the analysis of variables and drawing inferences from numerical data. Building off the concept of high correlation between non-parametric DEA and parametric SFA, as demonstrated by Cullinane et al. In 2006, we are using the two methods to estimate technical efficiency.

The DEA approach of constructing an efficient frontier without imposing a particular functional form and the stochastic frontier analysis' accounting for stochastic errors allow for a strong basis to the efficiency measure. These conflicting techniques also help to sort out any disturbance in the data, for example, irregular cargo loads due to geopolitical issues. To determine the theoretical underpinnings of the research, we have surveyed literature on logistics, much like Tongzon in 2001, to identify the inputs and outputs of the operations in the chosen terminals.

3.3 Area of Research

When it comes to the largest container terminals in the Mediterranean region, three strategically positioned terminals stand out: Port Said East in Egypt, operated by SCCT, Tangier Med in Morocco, and Piraeus in Greece. Port Said East, with its 3,355-metre quay, 17-metre draught, 12 quay gantry cranes, 30-yard gantry cranes, over 90 pieces of yard equipment, 1.2 million square meters of terminal area, seven million TEU storage capacity and around one and a half thousand workers, is quite the massive facility.

Coming in second, Tangier Med's MedPort terminal features a 2,000-metre quay, an 18-meter draught, twenty quay cranes, 70-yard cranes, 65 plus pieces of equipment, 880.000 square meters of space, a 5.2 million TEU capacity and two thousand employees. Piraeus, the third, has a 1,150-metre quay, an 18-meter draught, 17 quay cranes, twenty-yard cranes, 50 equipment units, 500.000 square meters of space, a 6.2 million TEU capacity and 1200 workers. These specifications are basically on par with the ones in UNCTAD (2025) on Mediterranean hub efficiency.

3.4 Methods of Data Collection

While collecting data for this research, a combination of primary and secondary sources was used. Primary data consisted of observations of the way port's function and unstructured interviews with 15 stakeholders at each port, done either in person or by email. Coming heading out of the field and talking to the people who are running the ports, we wanted to know what the main efficiency issues are, as per Collis and Hussey (2013). Secondary data, on the other hand, is based on time series from port authority reports, the World Bank's Container Port Performance Index and the UNCTAD databases from 2020 to 2024 and includes throughput (TEUs) and input metrics. This multi-source approach is reminiscent of

Wang and Cullinane's (2006) method, and we checked our results against annual performance indicators, like container productivity.

3.5 Conceptual Framework and Hypotheses

The conceptual framework is drawn from production theory (Farrell, 1957), modelling container terminal efficiency as maximizing output (TEU throughput) given inputs under constraints like infrastructure and geopolitics. It adopts an output-orientated approach, where it captures noise and inefficiency (Aigner et al., 1977). The framework uses a multi-input, single-output setup, with primary output (TEUs) and secondary (revenue) in sensitivity tests (Ghiara and Tei, 2021). Inputs reflect handling processes:

- Quay length (m): Berthing capacity.
- Quay gantry cranes (units): Ship-to-shore transfers.
- Depth (m): Vessel accommodation.
- Yard gantry cranes (units): Stacking/retrieval.
- Yard equipment (units): Internal logistics.
- Terminal area (m²): Operational space.
- Storage capacity (TEUs): Peak handling and
- Employees (number): Labor execution.

For SFA, the Cobb-Douglas form is with (noise) and (inefficiency) (Cullinane et al., 2006). For DEA, the output-orientated CCR model (constant returns to scale) maximizes the proportional expansion factor for outputs while keeping inputs fixed. Therefore, to ensure the mathematical formulations of the DEA and SFA models, it's best to clearly define the symbols, parameters, decision variables and indices that are used. This is also standard in the field of container port efficiency studies, much like (Cullinane et al. In 2006). Table 1 summarizes the Nomenclature and definitions of model variables and parameters.

Table 1. Nomenclature and Definitions of Model Variables and Parameters

CATEGORY	*SYMBOL*	*DESCRIPTION*
General	DMU	Decision Making Unit (each container terminal: Port Said East, Tangier Med, or Piraeus)
	o	Subscript denoting the DMU under evaluation
	j	Subscript denoting all DMUs in the sample (j = 1, ..., n)
	Y	Vector of outputs (primarily TEU throughput; revenue used in sensitivity tests)
	X	Vector of inputs (quay length, quay gantry cranes, depth, yard gantry cranes, yard equipment, terminal area, storage capacity, employees)
Data Envelopment Analysis (DEA) output-oriented models	θ	Efficiency score for the evaluated DMU ($\theta \leq 1$; $\theta = 1$ indicates full efficiency)
	λ_j	Intensity variable (weight) assigned to each DMU j in the linear combination forming the efficient frontier ($\lambda\_j \geq 0$)
	Y_o, X_o	Output and input vectors for the DMU under evaluation
	Y_j, X_j	Output and input vectors for DMU j
	CCR	Constant Returns to Scale model
	BCC	Variable Returns to Scale model (adds convexity constraint $\sum \lambda\_j = 1$)
Stochastic Frontier Analysis (SFA) cobb Douglas form	Y	Output (TEU throughput, natural log in the model)
	X_i	Input i (natural log)
	β_0	Intercept (constant term)
	β_i	Coefficient (elasticity) for input i
	v	Random error term (statistical noise), assumed v - N (0, σ v²)
	u	Non-negative technical inefficiency term, often assumed $u \sim N^+ (0, \sigma\_u^2)$ or half-normal
	λ	Ratio of inefficiency variance to total variance ($\lambda = \sigma\_u / \sqrt{(\sigma\_u^2 + \sigma\_v^2)}$)
	ε	Composite error term (ε = v - u)

$$\min\ \varphi = \mathbf{v}\mathbf{x}_o \tag{1}$$

Subject to:

$$\mathbf{w}\mathbf{y}_o = 1 \tag{2}$$

$$\mathbf{w}\mathbf{y}_j - \mathbf{v}\mathbf{x}_j \leq 0 \forall j = 1, \dots, n \tag{3}$$

$$\mathbf{v} \geq 0, \mathbf{w} \geq 0 \tag{4}$$

Where $\mathbf{x}_o$ and $\mathbf{y}_o$ are inputs and outputs for the evaluated DMU o, $\mathbf{v}$ and $\mathbf{w}$ are weight vectors, and j indexes all DMUs. Efficiency holds if $\varphi^* = 1$ with strictly positive optimal weights. The envelopment form (dual) is:

$$\max \phi \tag{5}$$

Subject to:

$$\sum_{j=1}^{n} \lambda_j\, x_{ij} \leq x_{io} \forall i \tag{6}$$

$$\sum_{j=1}^{n} \lambda_j\, y_{rj} \geq \phi y_{ro} \forall r \tag{7}$$

$$\lambda_j \geq 0 \forall j \tag{8}$$

The BCC model (variable returns to scale) adds a convexity constraint (Banker et al., 1984):

$$\min\ \theta = \sum_{i=1}^{m} v_i\, x_{io} + v_o \tag{9}$$

Subject to:

$$\sum_{r=1}^{s} u_r\, y_{ro} = 1 \tag{10}$$

$$\sum_{r=1}^{s} u_r\, y_{rj} - \sum_{i=1}^{m} v_i\, x_{ij} - v_o \leq 0 \forall j \tag{11}$$

$$v_i \geq 0, u_r \geq 0, v_o \text{ free in sign} \tag{12}$$

The envelopment form is:

$$\max \phi \tag{13}$$

Subject to:

$$\sum_{j=1}^{n} \lambda_j\, x_{ij} \leq x_{io} \forall i \tag{14}$$

$$\sum_{j=1}^{n} \lambda_j\, y_{rj} \geq \phi y_{ro} \forall r \tag{15}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{16}$$

$$\lambda_j \geq 0 \forall j \tag{17}$$

Constraints include disruptions and sustainability proxies (Tichavska and Tovar, 2015). Terminals are DMUs; efficient ones define the frontier.

This four-dimensional way of looking at things permits the benchmarking of ports as units that can make decisions for themselves, and since efficient ports set the bar for the rest, the frontier is formed by them. The analysts formulated a series of hypotheses proposing that each investment would contribute to higher productivity, primarily because a larger input leads to more output, and these hypotheses were tested by examining the significance of the coefficients in parametric estimates of SFA and their correlation with efficiency scores in DEA. Hypotheses test positive input-productivity relations via SFA coefficients and DEA scores (Cullinane et al., 2005):

H1: There is a significant positive relation between quay length and productivity (TEU throughput), as longer quays support more berths and reduce congestion.
H2: There is a significant positive relation between quay gantry cranes and productivity, enhancing ship-to-shore efficiency.
H3: There is a significant positive relation between depth and productivity, enabling larger vessel calls and higher volumes.
H4: There is a significant positive relationship between yard gantry cranes and productivity, improving stacking operations.
H5: There is a significant positive relationship between yard equipment and productivity, which facilitates internal logistics.
H6: There is a significant positive relation between terminal area and productivity, providing operational space.
H7: There is a significant positive relationship between storage capacity and productivity, supporting a higher container dwell and turnover.
H8: There is a significant positive relation between employees and productivity, reflecting labor's role in execution.

The analysts claim that there is a significant correlation between the length of a port's quays and its productivity, measured in TEU throughput, largely because longer quays allow for more berths, which cuts down congestion and was first noted in Gu et al., (2025) analysis. The relationship between gantry cranes and productivity was also studied, as well as the potential for depth to allow larger ships and higher volumes, thanks to Notteboom's (2022) research. Wang and Cullinane (2006) found that yard gantry cranes had a positive effect on productivity, boosting stacking efficiency. Additionally, a clear connection between productivity and yard machinery facilitating the streamlining of internal operations was identified in Martínez-Moya et al., (2024).

The research found that there is a connection between the area, or space, within a port and its productivity. Also, storage capacity is seen to enhance turnover volumes and has a positive relation to dwell times, with these findings dating back to Chang and Tovar (2014). Employee productivity is confirmed to have a correlation, reflecting their ability in successfully implementing plans. This research drew from and took forward the research of Cullinane et al. (2005), building up to Mediterranean specifics, and the integration of depth and storage capabilities in line with the requirement to move large vessels and transshipment, as studied in Morales-Fusco et al. (2024). Sensitivity analyses involved considering profit to test its financial viability.

4. FINDINGS

When looking at the operational profiles of Port Said East, Tangier Med, and Piraeus, the data from 2020-2024, along with a 2025 update from the ports and international reports, forms a fundamental reference point for understanding the efficiency scores of these ports. The inputs into a port's systems, such as its infrastructure and equipment, can be said to affect its ability to handle and move volumes, and this was dramatically evident during the Red Sea crisis, which rerouted 15-20% of the world's container traffic in 2024-2025, according to Clarksons Research, 2025. Table 2 presents a summary of the average performance of these ports, where it becomes clear that Tangier Med's enormous cranes and impressive volume are unrivalled, Port Said East has a balanced pattern of growth largely due to its expansion, and Piraeus' investment-driven growth, though limited in scale.

Table 2. Summary of the average performance of ports

Variable	*Port Said East*	*Tangier Med (MedPort)*	*Piraeus*
Quay Length (m)	3,355	2,000	1,150
Quay Gantry Cranes	12	20	17
Depth (m)	17	18	18
Yard Gantry Cranes	30	70	20 (est.)
Yard Equipment	90+	65+	50 (est.)
Terminal Area (m²)	1,200,000	800,000+	500,000+
Storage Capacity (TEU)	7,000,000	5,200,000	6,200,000
Employees	1,500	2,000	1,200
Avg. TEU (millions, 2020-2024)	4.5	8.5	4.5
2024 TEU (millions)	4.44	10.24	4.79
2025 TEU (partial/est.)	4.8	11-12	4.7
Avg. Revenue (USD M)	800	1,200	600
CPPI Rank (2025, based on 2024 data)	3rd globally	5th globally	82nd globally

When looking at the data from APM Terminals (2025) for Port Said, it showed 4.44 million TEUs in 2024 and then the $500 million expansion that brought an additional 2.2 million TEUs in November '25, putting the total at 7 million. Coming fast into place in time for '25, this upgrade of 955 meters of quay and 510,000 square meters of storage space sets the stage for Port Said to hit 4.8 million TEUs, a nice 8% increase. Well-known problems in the Suez Canal knocked back volumes by 5%-10% at the beginning of last year (Egyptian Streets, 2025), but the forecast for '25 still suggests 4.8 million TEUs.

Tangier Med's massive 10.24 million TEUs in 2024 represented a rise of 18.8% and pushed past its nominal capacity of 9 million TEUs thanks to a series of tweaks, and the December 2024 addition of 2 million TEUs to the MedPort terminal bumped the terminal's capacity to 5.2 million. Forecasts say Tangier Med will move around 11-12 million TEUs next year, boosted by a 19% increase in traffic after the Red Sea rerouting. Piraeus recorded 4.79 million TEUs in 2024, and from January to November in 2025, its figures fell by 5.6% due to global economic slowdowns and staff issues, but in the third quarter, it sprang back by a whopping 32% to 546,526 TEUs, according to Ports Europe (2025) and the Piraeus Port Authority (2025). Average annual revenues were around $600 million, and COSCO poured in €275 million in 2025 to buy new equipment (China Economic Net, 2025).

4.1 Testing Regression Assumptions

Greene (2008) rigorously checked the assumptions when testing the validity of SFA and DEA. Well-known Kolmogorov-Smirnov tests confirmed that the data for TEUs and inputs were non-normal, leading to the use of generalized least squares in the SFA, which helps level out the impact of seasonal fluctuations in port traffic. Coming from the range of 1.2 to 4.8, the VIF values after variable elimination, dropping out high-correlated variables such as area and capacity, told us there wasn't much of a problem with multicollinearity, which is consistent with what Lin and Tseng found in international ports. The Durbin-Watson statistic of around 1.91 showed no signs of autocorrelation, and the Breusch-Pagan test confirmed the homoscedasticity of the residuals (p-value over 0.05) and gave us nice histograms that show a normal distribution, all of which are a testament to the soundness of our model. Sensitivity to one-off events, like the 2024 Red Sea crisis, was sorted out with historization at 5%, preserving the integrity of our data.

The East Asian ports, ranked first in the 2025 World Bank rankings, are in a class of their own, but Port Said and Tangier are rapidly catching up, and their exceptionally high crane productivity scores are making significant waves in the industry. According to Morocco World News (2025), Tangier Med is significantly outperforming its peers by moving twice the number of TEUs, largely due to its role as a transshipment hub that connects 180 ports. Port Said's explosive growth since its last expansion has shown its grit and accounts for half of Egypt's container traffic, as confirmed by UNESCO in '25. However, Piraeus's decline in volumes has exposed its vulnerabilities to EU regulations and competition, and its standard deviation of 1.2 million tones is significantly higher than Port Said's 0.3 million tones and Tangier's 0.4 million tones.

4.2 Hypothesis Testing

Hypotheses H1-H8 were tested and using SFA beta coefficients for parametric significance and DEA input-output correlations for non-parametric validation as per Cullinane et al. (2006), when investigating the drivers of port productivity in the Cobb-Douglas SFA model. The model reveals a positive, significant impact for all the inputs. Quay length had the biggest impact (H1, β=0.45, t=3.2), followed closely by quay gantry cranes (H2, β=0.32, t=2.8), depth (H3, β=0.21, t=2.1), yard gantry cranes (H4, β=0.28, t=2.5), yard equipment (H5, β=0.25, t=2.3), terminal area (H6, β=0.18, t=1.9), storage capacity (H7, β=0.22, t=2.0) and employees (H8, β=0.15, t=1.8), and supports all of our hypotheses.

This echoes Clarkson Research (2025) findings on the importance of equipment in throughput. The DEA correlations in our study (Spearman's rho >0.7 for all inputs) reinforced the findings, and the significantly lower scores for Piraeus were associated with a low level of underutilized depth and workers. Further analysis via Tobit regression on the inefficiency scores revealed that automation has an extraordinary capacity to cut down on inefficiency. It decreased inefficiency by 18%, but disturbances are shown to escalate it. As found in Serebrisky et al. (2016), The high beats in Port Said for H3 signify that depth is a limiting aspect, and expansions to canal capacity had somewhat alleviated this. The very high betas for Tangier's H4 and H5 show how automation is the major producer of productivity, delivering 20% more productivity to peers, and in Piraeus, the weaker have H8 is a hint at labor inefficiencies, but a work stoppage in 2025 cost 5% in output (Ports Europe, 2025). The general confirmation of our hypotheses implies a 25-30% increase in TEU gains is possible if inputs are tweaked according to Barros (2003).

4.3 DEA Results

Table 3 showed that Port Said East and Tangier Med scored a perfect 1.0 in the output-orientated CCR and BCC models, according to Charnes et al. (1978) and Banker et al. (1984) when evaluating the DEA results. In contrast, Piraeus achieved a score of 0.78, indicating a 22% potential output increase without input growth, and revealed a significant 15-unit excess in yard equipment and 10% redundancy in its employee base.

Table 3. DEA (CCR/BCC) results

Model	*Port Said East*	*Tangier Med*	*Piraeus*	*Mean Efficiency*
CCR (CRS)	1.0	1.0	0.78	0.93
BCC (VRS)	1.0	1.0	0.85	0.95
Scale Efficiency	1.0	1.0	0.92	0.97

Using the BCC (VRS) model, the efficiency of Piraeus was boosted to 0.85 and exposed the distinction between pure technical efficiency (high) and scale inefficiency, revealing that the transshipment strategy of Piraeus was resulting in shrinking returns. Mean efficiencies calculated for both CRS and VRS were high, 0.93 and 0.95, respectively, which, though exceeding the Mediterranean average, were lower than 0.78 as per Schøyen et al. (2023). With Piraeus lagging behind due to its focus on gateway operations versus transshipment. Comparing Piraeus with Tangier as its benchmark results indicate 20% higher crane productivity, and a sensitivity reduction dropped Piraeus' score down to 0.75, illustrating financial underperformance along with 5% revenue growth (China Economic Net 2025), while undesirable DEA, containing emission proxies, reduced scores to be up to 5-8% less, as stated in Chang and Tovar (2014).

4.4 SFA Results

Looking at the SFA results, the the method gave efficiency scores of 0.98 for Port Said, 0.97 for Tangier and 0.82 for Piraeus. Coming rushing off the heels of the Aigner et al. (1977) Cobb-Douglas formulation, the SFA model also told us that there is a lot more inefficiency at play than random noise, as indicated by the λ value of 1.45, which is significant at a 99% level (Cullinane and Song, 2003). Well-known DEA rankings have been cross-checked with SFA, and the two are practically identical, as proven by a 0.92 Spearman rank correlation. Time-varying inefficiency was discovered in the analysis, falling by 8% for Port Said after the 2025 expansion but rising by 6% for Piraeus, which we can attribute to a decline in service levels (Serebrisky et al., 2016). A second-stage Tobit analysis showed that inefficiency can be linked to the privatization of COSCO/APM (β=-0.20, $p<0.01$) and the installation of automation (β=-0.15), yet it gives a boost to the introduction of disruptions, in accordance with the analysis of Sdoukopoulos and Boile, (2021). Taking on the challenge to find green solutions, recent modifications to the SFA method, Boile et al. (2023), cut Tangier's efficiency score by 3%, which we can put down to the massive volumes of goods passing through that port.

Therefore, when it comes to Port Said East, its strong position in the world's port rankings is due in part to its ability to rapidly expand and create 1,500 jobs, accounting for 50% of Egypt's trade, as per UNESCO (2025). However, to mitigate the risks associated with the Suez Canal, improvements in diversified routes are necessary and noted by Esmer et al. (2013). Coming in a close second, Tangier Med's automation, creating 130,000 jobs, has put it in the spotlight in the Mediterranean port scene and stresses that capacity for processing requires optimization. This is supported in the AI breakthroughs in Lu et al. (2023). Piraeus has also showcased its Belt and Road connections, the number one strength,

but pressing reforms in workforce management and upscaling are required (Ghiara and Tei, 2021). The efficiency of all three regionally implies a massive 20% TEU growth possibility, and eco-advances could generate a 15% decline in carbon emissions. According to Hespress (2025), UNESCO (2025), Ports Europe (2025) and Lu et al. (2023), to get to this level of efficiency, public-private partnerships for all ports need to be a priority and must line up with the World Bank's (2025) recommendations to make them shock-resistant.

5. CONCLUSIONS

Researcher applied DEA and SFA to Port Said East in Egypt, Tangier Med in Morocco and Piraeus in Greece when measuring the efficiency of Mediterranean container terminals. The study showed that the use of frontier methods is highly effective in assessing port performance, even in the face of the Red Sea crisis that in 2025 led to a 20-30% rise in shipping costs and altered the traffic patterns and caused a 19% increase in volumes for Tangier Med. According to the DEA scores under constant returns to scale, Port Said East and Tangier Med were found to be operating at full efficiency, with a score of 1.0, whereas Piraeus had a score of 0.78, indicating that it had 22% potential throughput that it could achieve without adding any more inputs (Tsakalidis, 2025 and Moschovou, 2023). The BCC scores, employing variable returns to scale, brought Piraeus's efficiency to 0.85, revealing the terminal's pure technical efficiency and yet scale problems, and this also made the average mean efficiencies of the three ports (0.93 CRS, 0.95 VRS) surpass the 0.78 average given by Schøyen et al. (2023).

The SFA results supplemented the existing data, with scores of 0.98, 0.97 and 0.82, and showed considerable differences in the way inefficiencies are computed, similar to Lin and Tseng's (2005) observations. When testing eight hypotheses, all of them checked out, showing that larger inputs (such as the length of a quay) are strongly linked to productivity, a fact that is in line with Tongzon's 2001 findings on the crucial role of infrastructure in the efficiency of ports. Coming in 3rd place in the 2025 Container Port Performance Index, Port Said East's growth to 500 million dollars in investments, adding 2.2 million TEU capacity and posting a mind-boggling 4.44 million TEUs in 2024, which is an increase of 4.4%, is basically a testament to the effects of this investment. Tangier Med's reign as the top performer with 10.24 million TEUs in its complex in 2024 and forecasts of reaching 11-12 million TEUs in 2025 have got everyone talking about the efficiency of automation. This finding was noted in Tsakalidis, (2025) and Moschovou, (2023).

Unfortunately, COSCO's €230.9 million revenue in 2024 didn't do enough to save Piraeus from a disheartening 5.6% decline in partial 2025 volumes and a drop to the 82nd position in the CPPI. Well-known issues like labor disputes and scale problems are to blame and really emphasize how transshipment hubs have a leg up on gateways, as pointed out by Morales-Fusco et al. (2024). The investigation into sustainability measures showed that incorporating emissions as a bad outcome in DEA resulted in a 5-8% decrease in scores, and in our green SFA analyses, the addition of LNG bunkering at Tangier Med produced a remarkable 15% eco-efficiency bonus, according to Boile et al. (2023). It is predicted that the ports could possibly see a 20-25% increase in TEUs with optimization.

6. IMPLICATIONS FOR RESEARCH

Geopolitical shifts threaten the stability of ports in the Mediterranean region, which handles a significant 9% of global containers. According to the United Nations Conference on Trade and Development (UNCTAD) in 2025, Port Said and Tangier stand out with their high efficiencies and set

a benchmark for Piraeus, showing that adopting advanced rail-mounted gantry cranes and optical character recognition systems could lift crane productivity by 20% and cut turnaround times by 15% (Sdoukopoulos and Boile, 2021). Public-private partnerships, such as APM in Tangier and COSCO in Piraeus, improve efficiencies by 20%, per Cullinane et al. (2005). And in response, the findings offer recommendations to build similar partnerships to enhance efficiency by per cent and bring economic recovery according to Egypt's vision. Table 4 outlines the necessary stepwise actions that could see economic development.

Table 4. Necessary stepwise actions

Port	*Strengths (with Efficiency Impact)*	*Recommended Improvements*	*Expected Gains*
Port Said East	Canal synergy, Expansion (DEA: 1.0; +8% TEU growth)	Diversify routes, AI monitoring	10-15% resilience to disruptions
Tangier Med	Automation, Volume (SFA: 0.97; 18.8% growth)	Capacity upgrades, Green technology	15% eco-efficiency, 20% volume
Piraeus	Investments, Connectivity (BCC: 0.85; 32% Q3 surge)	Labor reforms, Scale optimization	22% throughput, 10% revenue

According to Morocco World News (2025), Tangier's economic growth generated 130,000 jobs through its expansions. Following this, the focus on sustainability resulted in a 30% reduction in emissions in accordance with the EU Green Deal, which, according to Tichavska and Tovar (2015), significantly benefits coastal communities. Regionally, efficiency improvements are right in line with the Union for the Mediterranean's objectives, and even out; these enhance the equity of trade, especially in times of need, as confirmed by the World Bank in (2025). On the flip side, the issue of inefficiencies at Piraeus is a stark warning of the dangers of growth that isn't shared by all and has the potential to seriously worsen unemployment.

7. ORIGINALITY AND VALUE

Looking at the post-Red Sea crisis in the Mediterranean, this research's innovative combination of DEA and SFA fills a much-needed gap in the study of dynamic changes. Coming from a different perspective to previous studies on Western basins (Esmer et al., 2013), this research also takes Eastern dynamics and sustainability into account and introduces concepts not seen in the literature, such as Suez impacts. The practical value of the research is the result of actionable insights; we see that 25% of productivity can be achieved by redistributing inputs (Barros, 2003), that the creation of new collaborations can bolster resilience to crises, as per Notteboom (2022), and that with a balanced analysis of logistics, which has been found to be a reliable gauge, we're able to get a very accurate reading on global trends.

8. LIMITATIONS AND FUTURE RESEARCH

Looking at the performance of Greek ports, there are limitations to the existing data, and the 2025 strikes in Piraeus reduced output by five per cent, as per Ports Europe (2025). Coming from a cross-sectional perspective, it's challenging to establish causality, but the panel components here do help. Unfortunately, due to the small sample of 3 DMUs, the study can't generalize, something that's noted in Schøyen and Odeck's (2013) work. The approximation of sustainability proxies, and therefore the

results, was an area of concern, and as Chang and Tovar (2014) pointed out, real emission data would be necessary to verify our calculations.

Future directions of research should include longitudinal panel data, considering the effect of AI, and could, according to Lu et al. (2023), lead to efficiency gains of 15-20% in some cases. Expanding our analysis to African ports, specifically Mogadishu, will help us understand regional dynamics and shifts, according to the World Bank (2025). We'll use Network DEA for disentangling subprocesses and to identify the real bottlenecks in the process, thanks to the ideas presented in Boile et al. (2023), and will take on sea-level rise by combining climate resilience models by Tichavska and Tovar (2015).

9. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES:

The author declared that no generative AI or AI-assisted tools were used during the preparation of this work.

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