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Efficiency Analysis of Turkish Container Ports: SFA or DEA?

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ABSTRACT

Purpose: The study compares the efficiency of Turkish container ports using Stochastic Frontier Analysis and Data Envelopment Analysis. It aims to provide comparative insights for enhancing ports' operational performance. Capacity utilization and operational performance were analyzed in detail through ratio analysis.

Methodology: Two efficiency measurement techniques were employed: SFA evaluates efficiency by accounting for random errors and external factors, while DEA assesses relative efficiency by comparing ports to the best performers. Ratio analysis was used to evaluate capacity utilization through current handling capacity and annual growth rates.

Findings: Significant differences were observed between SFA and DEA results. Ports like MIP MERSİN and EVYAP demonstrated high efficiency in both methods, while discrepancies were detected in ports like MARDAŞ and ÇELEBİ BANDIRMA. SFA better captures external factors and operational challenges, whereas DEA emphasizes relative efficiency. For instance, MARDAŞ exhibited rapid growth in handling volume but low operational efficiency. Ratio analysis showed varying capacity utilization levels, with some ports operating near full capacity, while others, like AKÇANSA, operate at low capacity and need operational improvements.

Originality: The study provides a holistic view of port efficiency by integrating SFA, DEA, and ratio analysis. It not only measures comparative efficiency but also examines ports' capacity utilization. Differences in efficiency measures were discussed, with SFA offering valuable insights into strategic improvements by effectively reflecting operational challenges and external factors.

Keywords*:* Capacity Utilization, Operational Performance, Ratio Analysis, Logistics Efficiency.

JEL Codes: C44, C67, R41.

Türk Konteyner Limanlarının Etikinlik Analizi: SFA mı DEA mı?

ÖZET

Amaç: Stokastik Sınır Analizi ve Veri Zarflama Analizi yöntemleriyle Türk konteyner limanlarının verimliliği karşılaştırılmıştır. Çalışma, limanların operasyonel performansını artırmaya yönelik karşılaştırmalı bulgular sunmayı amaçlar. Oran analizi ile limanların kapasite kullanımı ve operasyonel performansları detaylı incelenmiştir.

Metodoloji: İki verimlilik ölçüm tekniği kullanılmıştır: SFA, rastgele hatalar ve dışsal faktörleri dikkate alarak verimliliği değerlendirirken; DEA, limanları en iyi performans gösterenlerle karşılaştırarak göreli verimliliği ölçmektedir. Oran analizi, mevcut elleçleme kapasitesi ve yıllık büyüme oranlarıyla kapasite kullanımını değerlendirmek için kullanıldı.

Bulgular: SFA ve DEA sonuçları arasında önemli farklılıklar gözlenmiştir. MIP MERSİN ve EVYAP gibi limanlar her iki yöntemde de yüksek verimlilik gösterirken, MARDAŞ ve ÇELEBİ BANDIRMA limanlarında yöntemler arasında farklar tespit edilmiştir. SFA'nın dışsal faktörleri ve operasyonel zorlukları daha iyi yakaladığı, DEA'nın ise göreli verimliliği öne çıkardığı görülmüştür. Özellikle MARDAŞ limanı, hızlı elleçleme büyümesine rağmen düşük operasyonel verimlilik sergilemektedir. Oran analizi, limanların kapasitelerini ne kadar verimli kullandığını ortaya koyarak, bazı limanların tam kapasiteye yakın çalışırken, AKÇANSA gibi limanların düşük kapasite ile çalıştığını göstermiştir.

Özgünlük: Çalışma, SFA ve DEA'yı oran analizi ile inceleyerek limanların verimliliğine bütünsel bir bakış sunmaktadır. Böylece sadece verimlilik karşılaştırmalı ölçülmemiş, aynı zamanda limanların kapasite kullanımları ele alınmıştır. SFA'nın, dışsal faktörleri etkin şekilde dikkate alarak operasyonel performansı yansıtması, stratejik iyileştirmeler için değerli bilgiler sunmaktadır.

Anahtar Kelimeler*:* Kapasite Kullanımı, Operasyonel Performans, Oran Analizi, Lojistik Verimliliği.

JEL Kodları: C44, C67, R41.

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1. INTRODUCTION

Container ports are integral to the global supply chain, facilitating the movement of goods across international borders. In Türkiye, container ports serve as vital roles for trade between Europe and Asia. Evaluating the efficiency of these ports is essential for optimizing their performance and enhancing their competitive edge, particularly as global trade continues to evolve rapidly. Efficient port operations result in faster cargo handling, reduced vessel turnaround times, and lower operational costs, all of which strengthen competitiveness in the global market. By minimizing delays and maximizing throughput, efficient ports enable smoother supply chain operations, reducing the likelihood of bottlenecks and ensuring timely delivery of goods. This reliability not only strengthens trade relationships but also attracts more business, contributing to both national and regional economic growth. Specifically, efficient ports boost exports, support industrial sectors that rely on timely shipments, and create employment opportunities in logistics and related industries. In contrast, inefficient port operations can lead to increased costs, trade delays, and supply chain disruptions, negatively impacting economic growth and trade competitiveness (Cullinane et al., 2002; Talley, 2006; Panayides and Song, 2009).

Inefficiencies in supply chains, production processes, and logistics systems can lead to significant negative consequences in economic and trade environments. A primary effect is the lengthening of lead times, which refers to the period between the initiation of an order and its delivery. Prolonged lead times delay product availability in the market, resulting in disruptions that frustrate both consumers and businesses (Christopher, 2016, p. 4). Additionally, inefficiencies often lead to inventory buildup, as companies tend to overproduce or hold excess stock to mitigate uncertainties. This not only ties up capital but also increases storage and handling costs, making the entire supply chain less responsive and more expensive to operate (Slack and Brandon-Jones, 2020, p. 456). A lack of flexibility emerges as another critical issue, as organizations struggle to adjust to sudden changes in market demand. The rigidity caused by inefficient systems prevents firms from capitalizing on new opportunities or responding effectively to challenges, such as shifting consumer preferences or global trade disruptions. Thus, addressing these inefficiencies is crucial for businesses seeking to improve their market positions and for economies aiming to enhance trade performance.

In the context of port efficiency analysis, the use of Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA) has been extensively explored. Each method offers unique advantages based on the characteristics of the data and the analysis objectives. SFA, a parametric method, incorporates statistical noise and external factors—such as environmental and economic conditions—into efficiency measurements. This capability makes SFA particularly valuable when such factors are significant and must be considered to avoid bias (Greene, 2005; Kumbhakar et al., 2015, p. 407). Conversely, DEA is a non-parametric method that assesses relative efficiency by comparing each port's performance against a "best-practice frontier" derived from the most efficient ports in the dataset. This method is especially effective in settings with multiple input-output relationships, requiring no assumptions about the functional form of the efficiency frontier (Coelli and Perelman, 1999; Thanassoulis et al., 2008, p. 251-420).

A comparative examination of these two basic approaches, SFA and DEA, has been a frequent focus in the literature, often applied to real and contemporary datasets containing both operational and physical characteristics of container ports. Such analyses provide a robust conceptual and practical basis for evaluating port efficiency (Karagiannis and Sarris, 2004; Jacobs et al., 2006; Strange et al., 2021; Theodoridis and Anwar, 2021). While both methods have their respective strengths, the choice between SFA and DEA depends on the specific analytical context. For instance, when the focus is on capturing random shocks or external noise in port operations, SFA might be the preferred method, while DEA is favored for its flexibility in handling multiple inputs and outputs without needing a pre-specified functional form (Lamb and Tee, 2024).

The rise of "smart ports" aims to enhance operational efficiency and competitiveness within the maritime industry. Container terminals are critical for international trade, leading the Korean government to invest in their technological advancements. However, research on the operational efficiency of these terminals implementing smart technologies is limited. The study analyzes 20 container terminals across five major ports using a Principal Component Analysis (PCA)–Data Envelopment Analysis (DEA) approach, finding that Ulsan Port and Busan Port (New) demonstrate the highest efficiency, particularly noting significant improvements at Ulsan Port (Zhou and Suh, 2024).

In conclusion, while SFA and DEA remain foundational methods in port efficiency analysis, emerging trends in the literature suggest the need for more integrated approaches that consider evolving operational challenges and environmental factors. This study contributes to the field by combining elements from both traditional and modern methodologies, applied to a real-world dataset that reflects the current state of port operations, infrastructure, and sustainability concerns.

This study addresses this comparison as a current and significant issue for assessing the effectiveness of container ports. It specifically focuses on handling operations, a critical component of ports' contributions to logistics, providing a practical analysis that is essential for strategic decision-making. Handling operations, which include the loading, unloading, and storing of containers, are key determinants of a port's throughput and, consequently, its efficiency. For instance, it has been shown that inefficiencies in handling operations can lead to significant delays and increased costs by Cullinane et al. (2002), making this a crucial area for efficiency analysis.

There are numerous studies examining the effectiveness of container ports in Türkiye (Ateş and Esmer, 2015; Acer, 2016; Akyürek, 2017; Çelik and Başarıcı, 2021; Aracıoğlu, 2022, p. 65). However, this study is unique in that it offers comparative results using both parametric (SFA) and non-parametric (DEA) methods, analyzing port efficiency in terms of handling outputs and considering the physical inputs of ports based on actual data. Additionally, ratio analysis assesses the proportion of current handling relative to handling capacity, as well as the year-over-year growth in handling, offering a clear indication of capacity utilization and improvements in operational performance. By utilizing a recent dataset, this study offers a comprehensive reflection of the current performance of Turkish container ports, informing strategic plans and policy decisions. This approach ensures that findings are relevant and aligned with contemporary operational challenges, allowing stakeholders to make informed decisions based on the latest trends and dynamics in the maritime sector. The integration of both SFA and DEA methodologies, alongside ratio analysis, enhances understanding of the factors driving port efficiency. This combined approach provides valuable insights into capacity utilization, operational performance improvements, and overall port efficiency, benefiting port administrations, transportation policymakers, and other stakeholders in the logistics sector.

The remainder of this paper is structured as follows: The literature review section presents a selection of studies examining and comparing efficiency analysis methods and port activities. The method section summarizes the conceptual structure of SFA and DEA, providing a clear explanation of how these methodologies are applied in the context of port efficiency analysis. In the analysis section, the data used and the organization of the data are discussed, followed by a presentation of the results obtained from the SFA and DEA analyses. Finally, the conclusion section interprets and discusses the results, addressing the limitations of the study and suggesting directions for future research. This structure ensures a logical flow from theoretical foundations to practical application, culminating in a set of actionable insights for improving the efficiency of Turkish container ports.

2. LITERATURE REVIEW

The evaluation of port efficiency has been extensively studied using various methodologies, with SFA and DEA being among the most frequently employed techniques due to their robustness in efficiency measurement. These methods have become essential tools in the analysis of port operations, allowing researchers and practitioners to assess the performance of ports in various contexts, from national economic planning to global supply chain optimization. Furthermore, integrating ratio analysis into these evaluations provides an additional layer of insight, particularly concerning capacity utilization and operational performance improvements.

SFA is a parametric approach that separates inefficiency from random noise within the production function. Introduced by Aigner, Lovell, and Schmidt (1977), SFA has been widely used in efficiency analysis across various sectors. This method models the production frontier by specifying a functional form and a distributional form for the inefficiency term, enabling the estimation of technical efficiency. Recent studies, such as Krljan et al. (2021), have applied SFA to assess the technical efficiency of interconnected container terminals, demonstrating its relevance in modern port operations. Moreover, the technical efficiency assessments of Turkish banks (Kantar and Yenilmez, 2017) and universities (Yenilmez et al., 2022; Yenilmez, 2024b) using SFA provide valuable references for similar applications in the port sector. SFA's ability to separate inefficiency from statistical noise makes it particularly useful in contexts where external factors significantly influence operational performance. Recent contributions have expanded the scope of SFA by incorporating novel distributional approaches to improve model flexibility and applicability. For instance, Yenilmez and Kantar (2019) introduced flexible error distributions within the SFA, providing a robust alternative for handling non-standard data behaviors, moreover, Yenilmez (2024a) explored the Lindley distribution in SFA.

DEA, developed by Charnes, Cooper, and Rhodes (1978), is a non-parametric method that evaluates the relative efficiency of decision-making units (DMUs) by constructing an efficient frontier from observed data. Unlike SFA, DEA does not assume a specific functional form for the production process, making it a versatile tool for efficiency analysis. DEA's flexibility has led to its widespread application in various fields, including port and logistics company efficiencies. Acer (2016) demonstrated the applicability of DEA in assessing the efficiency of Turkish ports, providing critical insights into areas where performance could be improved. Similarly, Lee et al. (2021) utilized DEA to evaluate the efficiency of logistics companies, showing how DEA can be adapted to different operational contexts within the broader logistics sector.

Comparative studies of SFA and DEA highlight the strengths and limitations of each method. For example, Theodoridis and Anwar (2011) compared SFA and DEA in the agricultural sector, finding that each method offers unique advantages depending on the data characteristics and analysis objectives. Similarly, Strange et al. (2021) applied both methods in the forestry sector, highlighting the robustness of SFA in accounting for environmental variability. Jacobs et al. (2006) explored these methodologies in the healthcare sector, emphasizing the importance of selecting the appropriate efficiency measurement technique based on the specific industry context. These comparisons underline the flexibility and applicability of SFA across different sectors, including ports. On the other hand, a comprehensive understanding of the methodologies' relative strength has been offered for DEA and SFA. In the banking sector, Nguyen and Pham (2020) conducted a comparative analysis of DEA and SFA, concluding that DEA's non-parametric nature allows for a more flexible evaluation of efficiency, particularly when the production process is complex and multifaceted. Lamb and Tee (2024) extended this comparison to investment performance, demonstrating that DEA can effectively handle diverse input-output relationships without the need for a predefined functional form, which is particularly useful in financial and investment analysis.

Incorporating ratio analysis alongside traditional efficiency measurement techniques like SFA and DEA offers a direct assessment of capacity utilization and operational performance improvements in port operations. Ratio analysis evaluates the proportion of current handling relative to handling capacity and measures year-over-year handling growth, providing essential insights into resource utilization. Panayides and Song (2009) emphasize that efficient capacity utilization is critical for a port's contribution to global supply chains, urging ports to monitor and optimize their capacity to maintain competitiveness. Talley (2006) also highlights the economic implications of port performance, noting that efficient capacity usage directly influences operational and financial outcomes.

SFA and DEA have applications in different disciplines, highlighting their versatility and relevance across various sectors. For instance, Öztürk and Yıldız (2016) discuss the significance of technical efficiency in health institutions and explore the application of SFA as a prevalent method for measuring technical efficiency by assessing the distance between the estimated best practice frontier and actual performance. They note the limited academic work on SFA in the Turkish health sector and aim to compile insights from international studies on its applications. The study reviews concepts of efficiency and frontiers, providing historical context, and presents a brief overview of the SFA method while contrasting it with DEA. Similarly, DEA and SFA have been extensively employed in assessing farm efficiency in Turkey, facilitating evaluations of technical efficiency and productivity across agricultural practices. Dudu, Cakmak, and Öcal (2015) analyze the efficiency structure of Turkish agriculture at the farm household level using SFA, revealing reliance on land and excessive labor, with regional disparities in efficiency. Cobanoglu (2013) investigates cotton farm efficiency using SFA and DEA, finding that SFA provides higher estimates, indicating the need for tailored agricultural policies. Kinaci, Najjari, and Alp (2016) extend these methodologies to evaluate hydroelectricity centers, emphasizing the importance of efficient resource use in enhancing productivity. The studies underscore the value of DEA and SFA in understanding efficiency to improve productivity and sustainability.

The efficiency of Turkish ports has been the subject of numerous studies, reflecting the critical role of these ports in Türkiye's trade and economy. Ateş and Esmer (2015) investigated the efficiency of ports in Türkiye using various methodologies, providing a comprehensive overview of port performance and identifying key factors that influence efficiency. Aracıoğlu (2022) specifically examined container terminal efficiency using DEA, highlighting areas where Turkish ports could improve their operational performance to better compete on the global stage. Akyürek (2017) focused on the efficiency of Turkish Black Sea ports, offering insights into the unique challenges and opportunities faced by ports in this region. This study emphasized the need for targeted strategies to enhance port efficiency in line with regional economic and logistical goals. Further, Çelik and Başarıcı (2021) evaluated port performance and criteria, emphasizing the importance of efficiency analysis for strategic decision-making. Their research highlighted how efficiency analysis could be integrated into broader strategic planning processes to optimize port operations and contribute to national economic development. By considering both the operational and strategic dimensions of port efficiency, their study provides a holistic approach to port management that is essential for navigating the complexities of modern global trade.

In summary, the existing literature demonstrates the significance of SFA, DEA, and ratio analysis in evaluating port efficiency. Each methodology offers unique strengths, and their application in various studies has provided valuable insights into the factors that drive port performance. The continued exploration of these techniques, particularly in the context of Turkish ports, will contribute to the ongoing efforts to enhance efficiency and competitiveness in this critical sector.

This study compares SFA and DEA to assess the efficiency of Turkish container ports, offering insights into their operational effectiveness and determining the most appropriate methodology for this context. Additionally, ratio analysis measures the proportion of current handling to handling capacity and year-over-year handling growth, providing a direct measure of capacity utilization and operational performance improvements.

3. METHOD

This study employs both SFA and DEA to evaluate the efficiency of Turkish container ports. The SFA model is specified with a Cobb-Douglas production function, while the DEA model uses an input-oriented approach to measure efficiency. The data are sourced from the report published by the Turkish Port Operators Association (TÜRKLİM) in June 2024 (TÜRKLİM, 2024). Additionally, handling data presented in previous years' reports of TÜRKLİM, and handling data presented in the Report 2024 for pre-2024 have been cross-validated using the container statistics page on the Turkish Ministry of Transport and Infrastructure's maritime statistics website (Ministry of Transportation and Infrastructure, 2024).

Inputs can be categorized into operational and physical types. This classification allows for a more detailed analysis and better evaluation of the impact of each input on efficiency. Operational inputs may be considered as labor force, operational costs, energy consumption, the amount of electricity and other energy sources consumed, and vessel waiting time. Physical inputs may be considered as terminal area, berth length, equipment, storage capacity, etc. In this study, physical input information could be accessed during the time spent on data compilation and analyses were performed in this context.

It is stated that, including temporary operating permits, a total of 46 ports in Türkiye are authorized to serve container ships and their cargo; however, only 28 of these ports can provide such services (TÜRKLİM, 2024). On the other hand, the TÜRKLİM 2024 report indicates that the share of the total container handling by the public ports TCDD İzmir Port and TCDD Haydarpaşa Port has been steadily decreasing over the past ten years (while 10.5% of the total container handling was carried out by public ports in 2013, this ratio fell to 2.4% in 2023). The report also notes that as of 2023, approximately 95.9% of the total container volume, which reached 12.7 million TEUs (Twenty-foot Equivalent Units), was handled by TÜRKLİM member ports. Due to data accessibility, regular reporting, and their high share of total handling, it was decided to focus the analysis on TÜRKLİM member container ports in this study. However, despite being TÜRKLİM members, Limak İskenderun, DFDS, And Ulusoy Çeşme were excluded from the analysis. Information on cranes and other equipment was not available for these three ports. Additionally, container handling capacity data were inaccessible for DFDS and Ulusoy Çeşme, and draft information was also unavailable for DFDS. Nonetheless, the 20 ports included in the study account for 91.80% of the total handling, ensuring the representativeness of the sample used in the research.

Considering the cargo development (TEU) in ports handling containers in Türkiye for 2023, the total share of the ports subject to analysis is:

$$\frac{TÜRKLİM\ Total - (Limak\ İsk., DFDS, Ulusoy\ Çeş.)}{TÜRKİYE\ Total} = \frac{12243032-521509}{12767934} = 0{,}918 \tag{1}$$

In this analysis, the outputs are the annual container handling values of the ports in TEUs. The inputs include the total areas of the ports, berth lengths, draft values, number of cranes, number of other equipment, and container handling capacities (in TEUs). In this analysis, the selection of inputs is based on their direct impact on port efficiency, as supported by various studies in literature. Total port area is a key factor, as larger areas generally allow for increased operational capacity and more efficient container traffic management (Cullinane et al., 2002). Similarly, berth lengths play a crucial role in port efficiency; longer berths enable ports to accommodate larger vessels, which enhances container handling capacity (Wang et al., 2003). Another important input is draft value, which determines the size of ships a port can service. Deeper drafts allow ports to handle larger ships, thereby increasing throughput (Turner et al., 2004). The number of cranes and other equipment is also vital, as it directly affects a port's cargo handling speed and overall performance. Ports equipped with more cranes can achieve faster turnaround times, improving their operational efficiency (Cullinane and Song, 2006). Lastly, container handling capacity (in TEUs) is a direct measure of a port's efficiency, reflecting its ability to process large volumes of containers. Ports with higher capacities are generally more efficient in handling cargo (Barros and Athanassiou, 2004).

In this study, SFA and DEA are used to evaluate the efficiency of DMUs based on selected inputs and outputs. Specifically, the CCR (Charnes, Cooper, and Rhodes) model is applied in the DEA analysis, assuming constant returns to scale (CRS), meaning any proportional increase in inputs results in a proportional increase in outputs. The CCR model (Charnes et al., 1978) measures both technical and scale efficiency, making it suitable for cases where DMUs are believed to operate at optimal scale. In contrast, the BCC model (Banker et al., 1984) allows for variable returns to scale (VRS), which accounts for efficiency variations due to scale differences by separating pure technical efficiency from scale efficiency. For this study, the CCR model is used, assuming constant returns to scale, to assess overall efficiency, without considering scale size variations. This approach provides a comprehensive efficiency score by encompassing both technical and scale efficiencies, making it appropriate for the study's objectives.

An output-oriented approach is utilized in SFA. This method focuses on maximizing output given a certain level of input. Its stochastic nature allows it to account for errors and inefficiencies in production (Greene, 2008, p. 103). Typically, an input-oriented model is used in DEA. This approach aims to minimize input usage for a given level of output. However, DEA is flexible and can also be adapted to an output-oriented framework depending on the research goals (Coelli et al., 2005). Input-Oriented aims to minimize input usage, reduce costs, and enhance resource efficiency. Output-Oriented focuses on maximizing output, improving productivity, and enhancing service quality (Cullinane and Song, 2006). SFA takes stochastic errors into account, providing a broader perspective on outputs, distinguishing between noise and inefficiency (Hoff, 2007). DEA is a deterministic model that evaluates all inefficiencies as certain, which may overlook random fluctuations (Greene, 2008, p. 112).

SFA is an econometric method used to estimate production functions while accounting for random errors and inefficiencies. The model assumes a composed error term, which includes both a random error (reflecting statistical noise) and an inefficiency term. The general form of the SFA model can be expressed as:

$$\ln(Y_i) = \beta_0 + \sum_{j=1}^{n} \beta_j \ln(X_{ij}) + v_i - u_i \tag{2}$$

where Y_i is the output of the i-th decision-making unit (DMU), X_{ij} represents the inputs, β_j are the parameters to be estimated, v_i is the random error term, u_i is the non-negative inefficiency term (Battese and Coelli, 1995). The general form of the Cobb-Douglas production function for this case would be:

$$\ln(Y_i) = \beta_0 + \beta_1 \ln(X_{1i}) + \beta_2 \ln(X_{2i}) + \beta_3 \ln(X_{3i}) + \beta_4 \ln(X_{4i}) + \beta_5 \ln(X_{5i}) + \beta_6 \ln(X_{6i}) + vi - ui \tag{3}$$

where Y_i annual container handling value of port i (in TEUs), X_{1i} total area of port i, X_{2i} berth length of port i, X_{3i} draft value of port i, X_{4i} number of cranes in port i, X_{5i} number of other equipment in port i, X_{6i} container handling capacity of port i (in TEUs), vi random error term (captures statistical noise), ui non-negative random variable (captures inefficiency).

DEA is a non-parametric linear programming method used to evaluate the efficiency of DMUs by comparing their input-output ratios. In this study, the CCR model (Charnes et al., 1978), which assumes constant returns to scale, was employed. The model evaluates technical efficiency by minimizing input usage while maintaining output levels.

The mathematical formulation of the input-oriented CCR model is presented. Firstly, objective function is as follows:

$$\min_{\theta,\lambda} \theta \tag{4}$$

Subject to constraints:

$$\sum_{j=1}^{n} \lambda_j X_{ki} \leq \theta X_{ki}, \qquad k = 1, \ldots, m \tag{5}$$

$$\sum_{j=1}^{n} \lambda_j Y_{ji} \geq Y_{ji}, \qquad i = 1, \ldots, s \tag{6}$$

$$\lambda_j \geq 0, \qquad j = 1, \ldots, n \tag{7}$$

where θ is the efficiency score for the i-th DMU. Y_{ji} and X_{ki} are the j-th output and k-th input of the i-th DMU, λ_j are the weights assigned to j-th DMU. n is the number of DMUs, m is the number of inputs, and s is the number of outputs (Charnes et al., 1978). In our case, for ports ($n = 20$), the model incorporates six input constraints ($m = 6$) and one output constraint ($s = 1$). Equations (5) and (6) ensure that the input and output constraints are satisfied for each DMU, while Equation (7) enforces non-negativity of weights.

Both SFA and DEA can be used to analyze the efficiency of the ports based on the given inputs and output. The analysis was conducted using R, a widely-used software for statistical computing and data analysis. Descriptive statistics, including mean, maximum, minimum, and standard deviation, were calculated for the dataset. The results of these descriptive statistics are presented in Table 1. The dataset was compiled from TÜRKLİM (2024) and Turkish Ministry of Transport and Infrastructure (2024)'s maritime statistics websites. Due to lack of permission, the raw data cannot be shared; however, variable and port information can be accessed from the values provided at the specified websites. Moreover, the compiled dataset is available to researchers upon request from the author.

Table 1. Desctiptive Statistics

Descriptive Statistics	Container Handling Values	Total Port Area	Berth Length	Draft Value	Number of Cranes	Container Handling Capacity
Kurtosis	-0.12	2.10	-0.11	1.12	-1.04	-1.53
Variance	1.00	2.00	3.00	4.00	5.00	6.00
Skewness	1.05	1.69	0.81	1.35	0.58	0.28
n	20.00	20.00	20.00	20.00	20.00	20.00
Minimum	2341.00	89750.00	450.00	9.50	7.00	60000.00
Standard Error	129278.50	67997.34	170.97	1.46	3.62	192472.60
Trimmed Mean	502431.80	374495.10	1419.63	16.93	22.75	1119063.00
Median	503267.00	382500.00	1329.50	16.50	20.00	1000000.00
Median Absolute Deviation	550042.40	161345.40	727.96	2.97	17.05	1074885.00
Standard	578151.00	304093.40	764.61	6.53	16.18	860763.70
Mean	586074.80	438779.60	1510.40	17.87	24.55	1162650.00
Range	1947541.00	1160250.00	2920.00	26.50	49.00	2540000.00
Maximum	1949882.00	1250000.00	3370.00	36.00	56.00	2600000.00

According to the Table 1, the kurtosis values indicate the distribution shapes; for instance, Container Handling Values (Co. Ha. Va.) and Total Port Area (To. Ar.) show near-normal distributions, while others exhibit more pronounced tails. The variance (Var.) values indicate the degree of dispersion, with Container Handling Capacity (Co. Ha. Ca.) exhibiting the highest variability, suggesting a diverse range of handling capabilities among the ports. The skewness (Ske.) values further elucidate this variability; notably, Container Handling Values (1.69) and Berth Length (1.35) display positive skewness, indicating a tendency towards higher values, while Draft Value (Dr. Va.) has a relatively low skew, suggesting a more symmetrical distribution. Minimum and maximum values highlight significant ranges across variables, particularly in Container Handling Values, which spans from 2,341 to 1,949,882 TEUs, indicating a vast disparity in operational capacities. The mean (Mea.) and median (Med.) values reveal that many variables, such as Total Port Area and Container Handling Capacity, are influenced by a few outliers, as evidenced by the large difference between means and medians. Overall, these statistics provide valuable insights into the operational characteristics and efficiencies of the analyzed ports, underscoring both their potential and variability in performance.

4. RESULTS

The efficiency scores obtained from SFA and DEA are analyzed and compared. SFA output-oriented and DEA input-oriented are used for different perspectives and robustness of findings. In other words, using both approaches together offers a rich and multi-dimensional understanding of efficiency. SFA can assess maximum outputs, while DEA can evaluate input efficiency, providing complementary insights. Comparing output-oriented SFA with input-oriented DEA can reveal discrepancies and provide a more comprehensive performance evaluation (Cullinane and Song, 2006).

SFA provides individual efficiency scores with confidence intervals, allowing for statistical inference. DEA offers a relative efficiency score, identifying ports that operate on the efficient frontier and those that do not. The results highlight the strengths and weaknesses of each port, providing insights into areas for improvement.

SFA Efficiency (SFA Eff) reflects efficiency scores based on a parametric approach, considering random errors. It provides a slightly varied understanding of operational performance under uncertain conditions. DEA Efficiency (DEA Eff) reflects efficiency scores based on a non-parametric approach, focusing purely on observed data without considering stochastic errors. It measures operational performance by comparing each port to the best performers, sometimes overlooking external inefficiencies or random variations. Moreover, two ratios are presented to deepen the analysis. Ratio (Handling Capacity) indicates the proportion of current handling to the port's handling capacity, providing a direct measure of capacity utilization. High ratios indicate effective utilization, while low ratios suggest underutilization. 23H/22H (Handling Growth) reflects the growth in TEU handled from 2022 to 2023, indicating year-over-year growth in handling volumes. High values suggest significant improvement in performance, while low values or declines indicate potential issues or stability. All results are presented in Table 2.

SFA output-oriented focuses on how much output (handling) a port can achieve given its current inputs (land, cranes, draft, etc.). This method incorporates random variations and external factors, making it a good tool to analyze maximum potential output under uncertain conditions. DEA input-oriented, on the other hand, assesses how efficiently the ports are using their inputs. By comparing ports to the best performers, DEA identifies the extent to which ports can improve their input use to achieve better performance, without considering randomness. Using both SFA and DEA together allows for a more comprehensive evaluation. SFA captures the potential output (handling), while DEA highlights the current input usage efficiency. The comparison of these two approaches reveals any gaps between the potential (what a port could handle) and the actual efficiency of resource usage (how efficiently it is operating). Ports with discrepancies between SFA and DEA scores might not be fully utilizing their capacity or may have external factors affecting performance.

According to DEA, MARPORT is utilizing its inputs at around 91.81% efficiency, meaning it could improve its input usage. From an SFA perspective, MARPORT has used only 57.75% of its potential handling capacity. This indicates that MARPORT is currently underutilizing its capacity and could handle significantly more cargo if operations were optimized. By comparing its current handling capacity with its theoretical maximum handling capacity using SFA, the potential capacity of MARPORT can be calculated. Ports like MARPORT, which demonstrate a gap between actual performance (DEA efficiency) and potential (SFA efficiency), can benefit from operational improvements and resource reallocation to boost their performance.

The results for SFA and DEA are also briefly presented in Figure 1. Figure 1 compares both current and potential capacities for each port would visually demonstrate the difference between what the ports are handling now and what they could handle if they operated at maximum efficiency. This helps in identifying underutilization areas and planning resource optimization.

For MIP MERSİN, both SFA and DEA scores show high efficiency. MIP MERSİN operates near optimal levels, effectively using its inputs and handling capacity. KUMPORT shows high DEA efficiency and good SFA efficiency, indicating well-functioning operations. Growth in handling volumes also suggests operational improvements. MARPORT displays moderate efficiency in both DEA and SFA. The handling growth indicates improving performance, but the lower ratio highlights the underutilization of capacity. Similarly, YILPORT has moderate efficiency scores but significant handling growth, suggesting improving performance with the potential for better capacity utilization. MARDAŞ exhibits significant differences between SFA and DEA scores, implying that external factors may be affecting its performance. Despite high growth in handling, its low efficiency suggests significant underutilization of capacity. ÇELEBİ BANDIRMA with the lowest efficiency scores in both SFA and DEA and a severe decline in handling, this port faces operational inefficiencies and capacity underutilization.

Table 2. Efficiency Scores and Ratios for Ports

No	Port	SFA Eff.	DEA Eff.	Ratio	23H/22H*
1	MIP MERSİN	0.9926	1.0000	0.7500	0.9648
2	ASYA PORT	0.5620	1.0000	0.6878	0.9569
3	MARPORT	0.5775	0.9181	0.6404	1.0990
4	KUMPORT	0.8273	1.0000	0.6072	1.0846
5	YILPORT	0.5694	0.8802	0.6399	1.1700
6	DP WORLD	0.5725	0.7773	0.5109	0.9837
7	EVYAP	0.9941	1.0000	0.7022	0.8821
8	NEMPORT	0.3901	0.7298	0.3367	1.0548
9	GEMPORT	0.3061	0.4078	0.2919	0.8625
10	EGE GÜBRE	0.5478	0.8528	0.5647	1.1028
11	MARDAŞ	0.1968	0.4717	0.2209	4.9800
12	SOCAR TERMİNAL	0.3586	0.7833	0.2880	1.0417
13	ASSAN	0.9936	0.9728	0.7295	1.4372
14	RODA PORT	0.9941	0.9074	0.6805	1.4428
15	BELDEPORT	0.4273	0.3689	0.2335	2.6053
16	SAMSUNPORT	0.9926	0.5552	0.4164	1.1780
17	BORUSAN	0.3380	0.2869	0.2151	0.7884
18	QTERMİNALS AKDENİZ	0.4942	0.3220	0.2415	0.9087
19	AKÇANSA	0.3904	0.2431	0.1823	0.6903
20	ÇELEBİ BANDIRMA	0.0316	0.0166	0.0125	0.2205

* 23H/22H indicates the ratio handled in 2023 to that handled in 2022 (in TEU).

Furthermore, Figure 2 compares the container handling values and handling capacities of various ports, measured in TEUs.The stacked bar chart shows the handling and capacity for each port, illustrating how close each port is to its maximum capacity. The red line and points indicate the utilization percentage, providing a clear view of efficiency. Ports with high handling values relative to their capacities suggest efficient operations, while those with lower utilizations may indicate underutilization or capacity constraints. This comparison is crucial for assessing port performance and identifying opportunities for improvement.

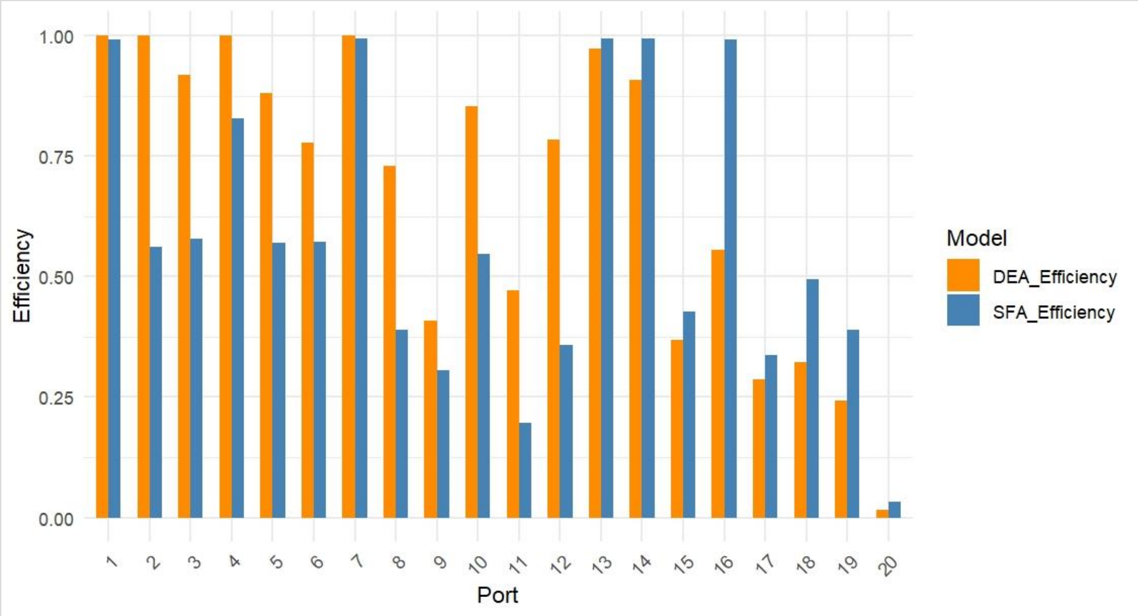

Figure 1. Comparison of efficiency scores

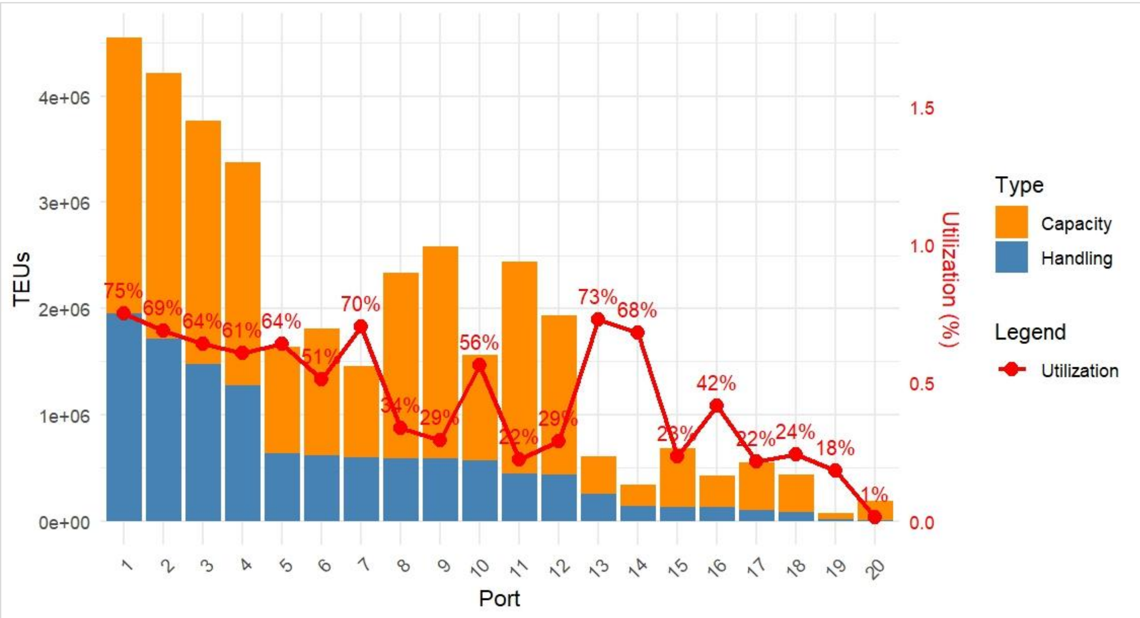

Figure 2. Comparison of container handling values of the ports and container handling capacity (in TEUs) and utilization (%)

5. DISCUSSION

The findings from this study indicate that while some Turkish container ports operate efficiently, others have significant room for improvement. SFA and DEA provide complementary insights into port efficiency. SFA's parametric nature allows for the separation of inefficiency and statistical noise, while DEA's non-parametric approach provides a flexible and data-driven assessment of relative efficiency. Recommendations for enhancing port efficiency include investments in infrastructure, better resource management, and adoption of advanced technologies. This section will also discuss which methodology, SFA or DEA, is more suitable for different aspects of port efficiency analysis.

By categorizing inputs as operational and physical, the impact of operational and physical inputs separately on the efficiency of the port can be analyzed. This aids in developing more targeted improvement strategies. Handling capacity is a crucial metric for evaluating port efficiency and is typically derived from several factors (Physical Infrastructure, Operational Processes, Historical Data), including the number of berths, cranes, and storage facilities available at the port. The capacity is often determined based on the maximum volume of containers that can be processed within a given timeframe (usually measured in Twenty-foot

Equivalent units- TEUs). The efficiency of loading and unloading procedures, the speed of transportation within the port, and overall logistical management play significant roles in determining how much cargo can be handled effectively (Operational Processes). Historical Data previous handling figures, combined with expected growth rates in trade volumes, can help estimate future capacity. Ports may use data from similar periods (like 2022 and 2023) to project handling capacity improvements or declines.

The efficiency scores derived from SFA and DEA reflect how well each port utilizes its inputs (resources) to produce outputs (handled containers). SFA provides a statistical approach to understanding efficiency by accounting for randomness and measurement errors, while DEA is a non-parametric method that assesses the relative efficiency of decision-making units without a defined error term. The Ratio presented (current handling to handling capacity) specifically measures how much of the available capacity is being utilized. While it is a useful indicator of performance, it only considers one input (current handling) relative to capacity, rather than a comprehensive view of all resources utilized. Simply comparing efficiency scores and ratios without considering the full context may not provide a comprehensive understanding of a port's performance. This may due to the following reasons (Narrow Focus, Efficiency Scores, Contextual Differences) The ratio only reflects current handling against capacity. It does not account for other operational factors such as labor efficiency, equipment downtime, and overall operational management. Therefore, two ports may have similar ratios but significantly different operational practices and resource utilization efficiency. Efficiency scores from SFA and DEA offer a broader perspective on performance by considering all inputs and outputs. This provides insights into how ports can improve beyond merely increasing the volume of containers handled. Different ports may have varying operational environments, regulations, and external factors influencing their efficiency. Comparing them solely based on one metric can be misleading.

The discrepancies between SFA and DEA scores observed in many ports illustrate the need for a more comprehensive analysis. For example, MARDAŞ shows an SFA efficiency score of 0.1968, compared to a DEA efficiency of 0.4717. This stark difference suggests that while DEA captures the relative efficiency compared to other ports, it may not account for certain operational challenges or external factors that SFA considers, such as random noise or external inefficiencies. In MARDAŞ's case, the lower SFA score indicates that it is operating far below its potential, and further investigation into the port's operational processes—such as equipment downtime or labor inefficiencies—could yield valuable insights into improving performance.

Similarly, ÇELEBİ BANDIRMA exhibits an extremely low SFA score of 0.0316 and an even lower DEA score of 0.0166, indicating significant inefficiencies across the board. The port's low performance in both methodologies may highlight potential systemic issues, such as aging infrastructure, inefficient logistics management, or underutilization of capacity. The 23H/22H growth ratio for ÇELEBİ BANDIRMA is 0.2205, showing a decline in container handling volume from 2022 to 2023, which further emphasizes the need for urgent strategic interventions to reverse this negative trend.

The Handling Capacity Ratio, which measures the current handling volume against the port's maximum capacity, varies significantly across the ports, shedding light on their efficiency in utilizing available resources. Ports like MIP MERSİN and EVYAP stand out for their high-capacity utilization. For example, MIP MERSİN has a ratio of 0.7500, indicating that it is utilizing 75% of its capacity. Coupled with its DEA efficiency score of 1.0000, MIP MERSİN is operating at peak efficiency, making it a benchmark for operational excellence.

In contrast, AKÇANSA has a much lower capacity utilization ratio of 0.1823, suggesting that it is only using 18.23% of its available capacity. Despite having a DEA efficiency score of 0.2431, the low capacity utilization may suggest significant underperformance, potentially due to external constraints such as low demand or operational inefficiencies within the port. This underutilization may point to a need for better alignment between the port's operational processes and its available infrastructure.

The 23H/22H ratio, which measures year-over-year growth in handling volumes, offers important insights into the operational progress of ports. MARDAŞ, for instance, shows a growth ratio of 4.9800, indicating nearly a fivefold increase in handling volume from 2022 to 2023. Despite this remarkable growth, its efficiency scores remain low (SFA: 0.1968, DEA: 0.4717), suggesting that while the port is handling more cargo, it is not doing so efficiently. This discrepancy highlights the need for MARDAŞ to focus not only on increasing volume but also on optimizing its operational processes to ensure that the increased activity is sustainable in the long term.

Similarly, RODA PORT shows significant growth, with a 23H/22H ratio of 1.4428, indicating a 44% increase in container handling year over year. With a relatively high SFA score of 0.9941 and a DEA score of 0.9074, RODA PORT demonstrates both operational growth and efficiency, positioning it as a well-functioning port that is leveraging its infrastructure effectively. This balanced performance may offer a model for other ports looking to improve both growth and operational efficiency.

The study also highlights ports where discrepancies between SFA and DEA scores suggest the presence of inefficiencies that may not be immediately apparent. YILPORT, for example, has an SFA efficiency score of 0.5694 and a DEA score of 0.8802. The relatively moderate SFA score, compared to the higher DEA score, indicates that YILPORT may have room to improve its operations, especially under uncertain conditions where external factors could be impacting its potential output. The handling capacity ratio for YILPORT is 0.6399, meaning it is using about 64% of its capacity, further suggesting that it has room for growth through better resource optimization.

Ports with similar performance profiles, such as MARPORT and DP WORLD, also show discrepancies between their SFA and DEA scores. For instance, MARPORT has an SFA efficiency score of 0.5775 and a DEA score of 0.9181. This difference indicates that MARPORT is relatively efficient compared to other ports but could still improve its handling operations, particularly under stochastic conditions. MARPORT's handling growth ratio of 1.0990 points to recent operational improvements, but the lower SFA score suggests it may still be underutilizing its capacity.

In contrast, DP WORLD displays both a low SFA efficiency score (0.5725) and a low DEA efficiency score (0.7773), coupled with a handling capacity ratio of 0.5109. This indicates moderate efficiency relative to other ports, but there is significant room for improving capacity utilization and overall performance. As with other ports showing similar profiles, DP WORLD would benefit from targeted investments in infrastructure and operational optimization strategies to enhance its performance.

The comparison of ports like GEMPORT and BORUSAN, which have some of the lowest efficiency scores, reveals significant underperformance. GEMPORT has an SFA efficiency score of 0.3061 and a DEA score of 0.4078, along with a handling capacity ratio of 0.2919. This suggests that GEMPORT is operating well below its potential and has considerable room for improvement in both operational efficiency and capacity utilization. Similarly, BORUSAN, with an SFA score of 0.3380 and a DEA score of 0.2869, may face serious challenges. Its handling capacity ratio of 0.2151 points to significant underutilization of resources, which could be a result of operational inefficiencies or external constraints limiting the port's performance.

Ports with similar underperformance profiles may benefit from strategic interventions, such as upgrading infrastructure, improving logistics management, and implementing advanced technologies like automation. By addressing these inefficiencies, ports can not only improve their current operations but also position themselves to better handle future growth in trade volumes.

The discrepancies between the SFA and DEA scores of ports like MARDAŞ and ÇELEBİ BANDIRMA highlight the importance of using both methodologies to capture a complete picture of port efficiency. By integrating the Handling Capacity Ratio and the 23H/22H growth ratio into the analysis, this study provides a slightly varied understanding of capacity utilization and operational growth, offering critical insights for policymakers and port authorities to make data-driven decisions. Ports that demonstrate both high efficiency and significant growth, such as MIP MERSİN, RODA PORT, and EVYAP, may serve as benchmarks for others to emulate. Meanwhile, ports with low scores, such as AKÇANSA and GEMPORT, may face the greatest challenges and stand to benefit the most from targeted operational improvements.

6. CONCLUSION

The conclusion of this study, which analyzes the efficiency of Turkish container ports using Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA), aligns with findings from previous literature. However, some inconsistencies highlight the need for slightly varied interpretations.

Firstly, the dual application of SFA and DEA reflects the broader literature on port efficiency, where both methods are often used to capture different aspects of performance. Cullinane et al. (2002) noted that SFA is advantageous for modeling inefficiencies influenced by external noise, while DEA provides a non-parametric measure of relative efficiency. This dual approach is used in recent studies by González and Trujillo (2009), which emphasize the importance of using both methodologies to capture the complexity of port operations. The results of this study reinforce these conclusions, demonstrating that ports such as MIP MERSİN perform well in both analyses, suggesting a well-balanced operation with minimal inefficiencies.

However, this study also identifies cases where DEA and SFA scores diverge, such as with MARDAŞ and ÇELEBİ BANDIRMA. Such discrepancies have been reported in other studies, including Barros (2006), where DEA may overestimate efficiency by not accounting for random shocks or external disruptions captured by SFA. This is particularly evident for ports with high growth rates but low efficiency scores, like MARDAŞ, which indicates rapid expansion without corresponding operational optimization. This finding aligns with research by Cullinane and Song (2006), which cautions against relying solely on DEA scores for ports undergoing rapid changes, as it may obscure deeper inefficiencies.

Additionally, the handling capacity ratios observed in this study, particularly for underperforming ports like AKÇANSA, provide a critical lens through which to assess port efficiency. Studies such as Tongzon (2001) have long emphasized the importance of capacity utilization as a key determinant of port efficiency. The low-capacity utilization ratios observed in ports like AKÇANSA and BORUSAN may suggest that internal inefficiencies, such as poor resource management or underdeveloped infrastructure, are hindering performance. These findings are consistent with Wang et al. (2003) work, which highlighted that ports with higher capacity utilization typically exhibit greater operational efficiency.

The year-over-year growth ratios (23H/22H) also play a crucial role in evaluating port performance, as growth without efficiency improvements can strain operations, a challenge noted in studies like that of Cheon et al. (2010). For instance, while RODA PORT demonstrates balanced growth and high efficiency, BORUSAN and GEMPORT may face challenges with both low growth and underutilized capacity, a scenario similar to that reported in studies of underperforming ports in developing regions (Notteboom and Winkelmans, 2001). These ports may benefit from targeted interventions, such as adopting new technologies or streamlining logistics operations, as suggested by recent literature on port modernization (Wang et al., 2013).

The discrepancy between SFA and DEA results for specific ports, such as YILPORT and MARPORT, underscores the importance of using multiple methodologies in port efficiency analysis. Relying on a single efficiency measure may overlook the impact of external factors like economic shifts or adverse weather conditions, which SFA is designed to capture. This study's findings highlight the necessity of incorporating both SFA and DEA to gain a comprehensive understanding of port performance.

In summary, this study contributes to the existing literature by reinforcing the complementary nature of SFA and DEA in port efficiency analysis, as demonstrated in similar studies (Cullinane et al., 2006; González and Trujillo, 2009). The use of additional metrics, such as the handling capacity ratio and growth ratios, further supports a multidimensional approach to evaluating efficiency, aligning with broader literature that emphasizes the complexity of port operations (Cheon et al., 2010; Wang et al., 2003). However, as previous research suggests, ports experiencing rapid growth, but low efficiency scores should undergo closer operational scrutiny to ensure sustainable improvements (Notteboom and Winkelmans, 2001). Future studies should build on this analysis by incorporating a broader range of input factors, including labor, technology, and external influences such as weather and trade patterns, to provide an even more slightly varied understanding of port performance. Tracking efficiency metrics over a longer period and benchmarking ports against global best practices could further enhance strategic decision-making for port management.

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The analyses in this study were conducted using publicly available data related to ports. The study exclusively interprets numerical values derived from scientific methods, without including specific judgments or evaluations of any port. Since the analyses do not involve subjective assessments and rely solely on publicly available data, no ethical approval was required. The authors assume no responsibility for any potential implications arising from the interpretation of numerical results based on publicly available data.

Conflict of Interest
No potential conflict of interest was declared by the author.

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Compliance with Ethical Standards
It was declared by the author that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement
It was declared by the author that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

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