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THE EFFICIENCY OF THE CONTAINER TERMINALS IN ADRIATIC: AN IMPROVED DATA ENVELOPMENT ANALYSIS

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Research Paper

Abstract: *Ports have a very important role in global trade networks and serve as a critical nodes for the transport of goods around the world, while their container terminals act as an important engines for local and regional development. However, port operations present challenges and complexities that require optimal management and strategic planning. This study focuses on evaluating the sustainability-based efficiency of the Adriatic container terminals using the Data Envelopment Analysis (DEA) method over the last three years. The proposed model ND-SBM-UO was developed for the case of uncontrollable inputs (ND) and undesirable outputs (UO). Indicators were defined to evaluate the efficiency of container terminals when there is no access to certain data. Indicators were also defined that were missing in previous studies, such as the degree of connectivity and the level of equipment of the terminals are also defined. In this way, efficient and inefficient container terminals, and the causes of inefficiency at individual container terminals are defined. The proposed model is used to identify efficient and inefficient terminals and their efficiency scores. In addition, this study will search for the reference container terminals and determine the causes of inefficiency of each container terminal based on the reference container terminals and returns to scale. The results of this study could be helpful when improving the efficiency and performance of the container terminals. This work will be of keen interest to research community and policy makers in the transport sector, exporters/importers of companies, and port authorities.*

Keywords: *Adriatic Ports, Container Terminal, DEA, Port Efficiency, Returns to Scale, Slacks Based Measure (SBM), Undesirable Output, Uncontrollable Input.*

1. Introduction

Maritime transport is very important for the export and import of goods, as this mode of transport has advantages over other modes of transport in terms of transport costs, speed, high loading capacity and accessibility to more distant areas. In addition,

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maritime transport reduces the usage of road and air transport, thus contributes to reducing air pollution and greenhouse gas emissions. Considering that, around 70% of world trade is carried by sea, maritime transport of goods is an important factor in the growth of the global economy. More than 80% of internationally traded goods is transported by sea, and in most developing countries the proportion is even higher. United Nations Conference on Trade and Development (UNCTAD) forecasts that maritime trade will grow by more than 2% between 2024 and 2028. The UNCTAD (2023) report emphasises the balance between environmental goals and economic needs. The industry must therefore move faster towards solutions to improve efficiency and sustainability. This means reducing pollution and increasing the efficiency of ports.

Container terminals are responsible for an important part of this transport, and the importance of container terminals is due to the facilitation of global trade, as they are the main hub of global trade. A standardised approach in container terminals reduces logistics costs. Proper management of container terminals helps to minimise the environmental impact (Wooldridge et al., 2025).

For Europe, maritime transport enables trade and communication between all European countries (Bakkar et al., 2025). Almost 90% of the EU's foreign trade is carried out by sea and short sea shipping accounts for a third of intra-EU trade in tonne-kilometres (UNCTAD, 2023). In general, the maritime industry plays a crucial role in providing employment and generating income within the European economy. The European Commission has set itself the goal of minimising the environmental impact of maritime transport and improving the economic performance of this industry (Transport, 2023).

The aim of this article is to perform the evaluation of the efficiency of container ports. In recent years, Adriatic container ports have developed considerably. The volume of container throughput in the Adriatic ports of Central and Eastern European countries increased from 9 to 18 million tonnes between 2015 and 2019 (Statista, 2023). This growth trend has taken place in the Adriatic ports in line with the growth of ports around the world. These factors are intensifying competition between ports, meaning that ports must improve their performance in order to survive in this global competition. In the long term, the Adriatic ports will expand their role in trade with countries such as the Czech Republic, Slovakia, and Hungary, but also with Austria, Germany, and Poland (OSW, 2023). To fulfil their ambitions, these ports need to improve their performance with minimal impact on the environment. Therefore, in this article we look at assessing the efficiency and sustainability of container terminals on the Adriatic Sea using a methodology based on DEA.

DEA is a mathematical methodology used to evaluate the efficiency of a selected decision-making units (DMUs). These units are described by several inputs and several outputs. With DEA, it is possible to evaluate efficiency even in the presence of undesirable outputs. The problem of undesirable outputs in the evaluation of transport systems is sometimes ignored. In cases where environmental efficiency is evaluated, environmental indicators are taken into account. The main objective of this study is therefore to assess and measure the efficiency of container terminals and perform their ranking while considering all undesirable indicators. Therefore, this research aims to evaluate the sustainability-based efficiency of container terminals in the Adriatic Sea using improved DEA models in the period of 2020 - 2022.

In other words, both the environmental and economic efficiency indicators are considered and an assessment model for overall efficiency is introduced that allows to simultaneously identify efficient and inefficient units. In order to perform the evaluation, we developed a model that takes into account undesirable outputs and uncontrollable inputs and evaluates performance accordingly. The Principal Component Analysis (PCA) method is also used to access the actual results. The reason for this is that the small number of units compared to the variables may influence the final result. Therefore, non-classical DEA methods are used in this study. We proposed the Slacks-based Model with UO and ND inputs (ND-SBM-UO), which is used in this study to evaluate and categorise or rank the performance of the units. In addition, this approach provides a method to identify a set of efficient units as a reference unit for improving inefficient units.

Although the ND-SBM-UO model was initially applied to container terminals in the Adriatic Sea, its design ensures robustness and broader applicability. Basing the model in a data-driven and quantitative approach provides flexibility to consider different operational contexts. The inclusion of non-discretionary variables and undesirable outputs reflects its ability to assess performance comprehensively and fairly. This makes the ND-SBM-UO model highly adaptable for use in other geographical areas or types of container terminals, particularly where environmental sustainability is a major concern. Future applications of the model could extend to terminals in regions with different operational sizes, cargo compositions and environmental regulations. The validation of the ND-SBM-UO model is supported by its ability to incorporate realistic constraints and variables inherent to container terminal operations. Moreover, the model has the potential to serve as a benchmarking tool that enables terminal operators and policy makers to identify best practices and set achievable performance targets.

This article consists of 9 sections. Section 2 offers the literature review, section 3 deals with an overview of the used DEA models for the calculation of efficiency of the selected DMUs, while the empirical case and results are presented in section 4. Section 5 is devoted to the discussions, while conclusions are drawn in section 6. Section 7 describes the limitations of the study, section 8 deals with the limitations, while future research directions are outlined in the final, section 9.

2. Literature Review

In recent decades, efficiency, economic and environmental analyses of ports have increased significantly. The DEA method is used more frequently in this area as compared to other methods. Due to its special characteristics, DEA is a suitable instrument for evaluation (Kishore et al., 2024). In the literature, more than 100 articles have used DEA to evaluate ports worldwide by 2021. The first study on port efficiency was published in 1993, where the DEA method was developed by (Roll & Hayuth, 1993) and was used to assess the efficiency of ports in Israel. Such assessments using DEA can be of highly informative for both researchers and port managers and give a deeper insight into port performance. Later, Martinez-Budria et al. (1999) extended this approach to evaluate Spanish ports using DEA.

Quintano et al. (2020) evaluated the efficiency of 10 major European ports between 2012 and 2016, and the results confirmed that policy measures can use this techniques to validate the potential impact of certain measures. Moreover, in this study classical DEA models were used as it was used by the other researcher. By developing an integrated model with a two-stage uncertainty DEA for the operational efficiency measurement of the 40 worlds' largest container ports over the period between 2013 and 2017, (Pham et al., 2021) demonstrated the possibility of carrying out a more inclusive evaluation of the performance of the container port through the combination of the two-stage DEA model with the FCM algorithm. Iyer and Nanyam (2021) aims at analysing the performance of 26 Indian container terminals and dividing them into two types: high performers and low performers, through the use of classical DEA models during 2015-2018. Their results can serve for port managers in the efficiency improvement of their terminals and in the increase of the scale of their operations instead of building new terminals. Using Delphi, KAMET and DEA modelling, (Nong, 2023) investigated the performance efficiency of ports in Vietnam, contributing to the research community with new integrated technique for port efficiency evaluation as in case of many different inputs and outputs. Danladi et al. (2024) focused on benchmarking container ports in developing regions using the DEA approach and provided valuable insights into the relative performance of ports in these countries. Their study emphasizes the importance of adapting efficiency assessment models to the specific conditions of low to middle-income countries, where ports often face different challenges than in more developed economies. Efecan and Temiz (2024) investigated the relationship between the physical size of container ports and their efficiency. Using an integrated approach combining genetic matching and stochastic DEA, the study found that larger ports tend to have a negative impact on efficiency, contradicting the general assumption that larger ports are always more efficient. The study emphasizes the importance of efficient management in smaller ports and suggests clustering ports according to certain characteristics to obtain more balanced benchmarks. Analysing 25 Chinese container terminals in 2019, Li et al. (2024) observed the averaged at 0.65 as moderately efficient production operations but had far lower values for transforming profits (0.23) and overall efficiency (0.35). Important factors that increased efficiency levels included service pricing and quality along with technological improvement, regional economic development, and larger investment size, while bigger investment sizes negatively affected it. Their model includes GHG emissions, terminal structure, and co-opetition dynamics as well as "peer-evaluation" to enhance accuracy and comparability. This approach gives vital insight along with practical strategies for improving the effectiveness and sustainable performance of container terminals.

Hsu et al. (2024) put forward a novel framework for sustainable efficiency evaluation at container terminals, which is based on the definition given by the UNCTAD, on business sustainable development, which considers economic, environmental, and social domains. Sustainable efficiency was analysed in terms of container throughput, CO_2 emissions, and occupational safety. Using a modality movement and fuzzy grey relational analysis (GRA), they have estimated CO_2 emissions, and occupational safety indices, respectively. Based on the holistic assessment of sustainable efficiency, they have proposed a hybrid (SBM)-DEA model. Their empirical study on CT operators at Port of Kaohsiung confirmed the proposed model as reliable and informative that could be vital in both theoretical and practical application for the advancement of CT management and port operations. This study is of importance since it integrates considerations of the environment and society in efficiency assessments. Thus, this paper provides a robust framework for sustainable decision-making in container terminal operations.

Hsu et al. (2024) looked into the eco-efficiency of container terminals (CTs) within ports by introducing unwanted outputs such as CO2 emissions into the efficiency evaluation process. The performance of CT operators was evaluated with the help of the SBM-DEA model and the modality movement approach, with a quantification of their CO2 emissions. According to the results, Wan-Han is the most efficient CT operator in the period from 2017–2019 with an average efficiency of 0.993. Moreover, the study proved that CO2 emissions significantly affect efficiency scores and that inefficient DMUs can improve their performance by reducing slack variables. Their study adds to the body of knowledge by focusing on greenhouse gas emissions in relation to operational efficiency and providing prescriptive guidelines.

Evaluation of the environmental management systems of 24 Italian ports in 2016 using a multistep approach based on official data was performed by (Castellano et al., 2020). Their results emphasize the importance of using a comprehensive framework for the assessment of environmental and economic performance at the same time, and thus avoiding partial assessments. Quintano et al. (2021) have attempted to assess also the performance of these ports in terms of their eco-efficiency by using DEA and SFA. From the results they concluded that the recent efforts to increase port activity made by the management doesn't impact the eco-efficiency of ports. A production analysis framework is proposed by Rødseth et al. (2020), to investigate "intertemporal changes in cargo volumes" and air pollution in the port. They analysed 9 Norwegian ports between 2010-2015 using input–output combinations of DEA. The study findings indicates that ship size is associated with higher pollution per berthing hour of air pollution, ship size with higher productivity in container handling and then to a possible lower dwell time of ships in port per loaded or unloaded container. Different theoretical frameworks are also offered to policy makers on how the specific measures may impact the eco-efficiency.

Spengler et al. (2024) investigated whether it is essential to include energy consumption variables and output disaggregation for significant efficiency analysis of container terminals. They used DEA to compare efficiency scores both without and with energy consumption as input and separate the case of dry and reefer container handling. It shows that considering output differentiation leads to significantly different efficiency scores, with arguments being firmly put forward for taking into account energy consumption and output differentiation in an analysis of terminal productivity. Their work provides a starting point for the incorporation of these variables in subsequent studies. This increases the accuracy and applicability of assessments on the efficiency of container terminals in the future. Chen et al. (2024) applied the SBM model in assessing the sustainability performance of 10 leading port cities within China from 2018 to 2021, considering dynamics and the influences of the COVID-19 pandemic that affected the efficiency of ports. The proposed model fills gaps in the literature by integrating both operational and environmental performance, which were often considered separately in previous DEA studies. The model treats emissions as undesirable outputs and provides a more comprehensive assessment of port efficiency and eco-efficiency. It also accounts for uncontrollable variables that have traditionally been overlooked in efficiency models. This inclusion provides a more realistic and robust assessment of port performance and helps policymakers and managers make informed decisions balancing efficiency and sustainability under different external conditions.

3. Research Methodology

This study applies an enhanced DEA model for evaluating the efficiency of container terminals in the Adriatic. The first step determines the input and output variables through opinions of port experts. The opinion of port experts in the Adriatic was collected by means of a questionnaire to determine the inputs and outputs. The PCA method is used to reduce the number of variables to solve the problem of the small number of DMUs. The reduction of variables helps to alleviate the problem of small sample size in DEA and provides more reliable and stable results. After applying PCA, the improved DEA model is used to measure the performance efficiency of the Adriatic container ports. In the proposed model, the non-radial SBM model is adjusted to account for undesirable outputs and uncontrollable inputs. The entire research process is illustrated in Figure 1.

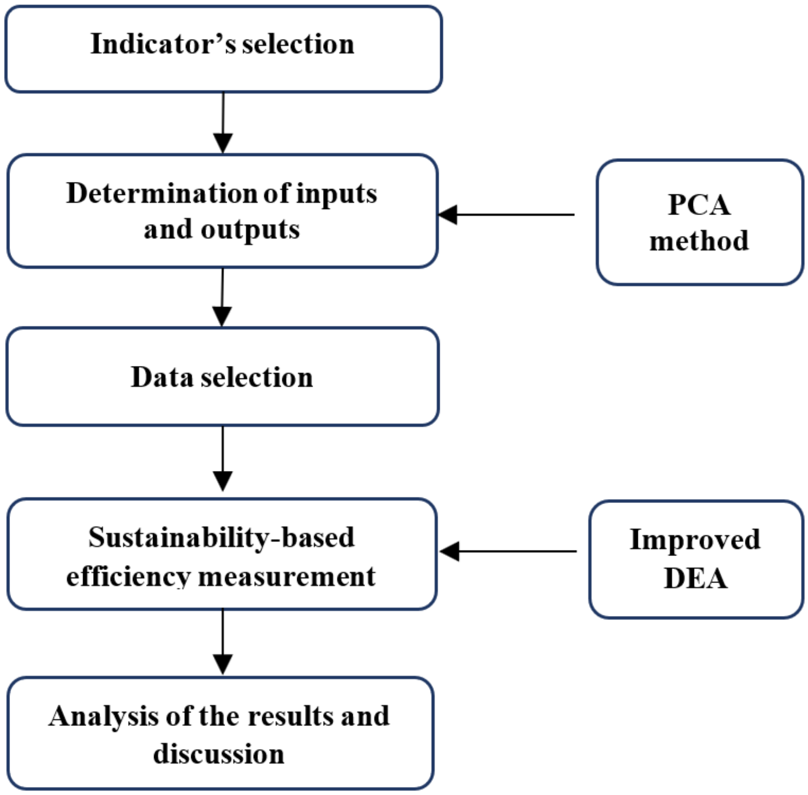

Figure 1: Research Process.

3.1 PCA Method

PCA is one of the methods of factor analysis which aimed to reduce the dimension of the problem to be analysed. With this technique, a large number of correlated explanatory variables (independent variables) can be replaced with a limited number of new dependent variables whose principal components (factors) are introduced and are uncorrelated (Greenacre et al., 2022; Ho & Wu, 2009). The basic principle of PCA is: search for "a linear combination of variables with maximum variance" and search for " a second linear combination of variables" that are independent of the first combination by maximising the residual variance and so on until the end (Golany & Roll, 1989). By using PCA, we can ensure that only the most important variables that contribute the most to explaining the variability of port performance are selected for the DEA model. This reduction helps to eliminate redundant or correlated variables that might otherwise distort the DEA results. In this study, PCA ensures that the DEA model remains stable and interpretable, leading to more accurate port efficiency assessments.

The application of PCA ensures that the dimensionality of the data is reduced, which increases the stability and reliability of the DEA efficiency scores. By focusing only on the most important components derived through PCA, the results of DEA analysis become more robust and overcome the challenges posed by small sample sizes associated with port efficiency assessment. This method helps to avoid the problems of multicollinearity and overfitting that could otherwise lead to unreliable performance evaluations. In this study, the main objective is to use PCA as a method to reduce the number of indicators, i.e., to solve the problem of the small number of units compared to the inputs and outputs. After the PCA was performed for the indicators in the analysed ports, our improved DEA model was then applied.

3.2 DEA Method

In 1957, the original idea for the development of DEA was proposed by Farrell. Later, Charnes et al. (1978) modified the theory and its calculations so that it became possible to use multiple variables as input and output. Due to the simplicity and effectiveness of the DEA analysis method, this technique is often used to check the efficiency of production or service units. Productivity is calculated on the basis of the fraction whose face is the output and the denominator is the input. Efficiency can therefore be seen as the ratio of output to input. The Data Envelopment solution was created on the basis of "linear programming" and is considered as a tool for measuring and comparing the efficiency of several DMUs, especially when the production process consists of an input and output structure.

3.2.1 SBM -UO Model

To address the limitations of classical DEA models, such as the CCR and BCC models, which are radial and focus primarily on the input-output relationships (Tsaples & Papathanasiou, 2021), the Slacks-Based Measure (SBM) model was introduced by (Tone, 2001), which incorporates slack variables. This non-radial model measures not only efficiency but also the inefficiencies as a result of many inputs or deficiencies in output. The SBM model is very effective for analysing systems with inefficiencies resulting from internal as well as external sources such as environmental effects or operational limitations.

In the new wave of port management where sustainability tops the list, undesirable outputs—such as emissions—must not be left out of efficiency evaluation. If such outputs are left out, misleading results will occur since they contribute significantly to assessing performance. Therefore, by considering undesirable outputs, the SBM model provides a more holistic evaluation of port performance, integrating both operational efficiency and environmental aspects. The issue at hand is specifically addressed in SBM-UO model where undesirable outputs are included in the framework of assessment. Assuming n DMUs, X as the input, and Y as the output, with m inputs, s1 desirable outputs, and s2 undesirable outputs (all nonnegative), the SBM-UO model is a linear programming problem (Tone, 2015).

3.2.2 ND-SBM-UO Model

In this part, we consider efficiency analysis for cases where there are uncontrollable inputs in the production process. In the real world, there are sometimes some of the input/output components that are not under the control of the system manager in the DEA. In these cases, a direct application of the model does not seem logical. To correctly evaluate management performance, it may be necessary to distinguish between controllable and uncontrollable inputs. For this reason, we have proposed and used a modification of SBM-UO model, namely ND-SBM-UO, where we assume that the input variables are divided into controllable (D) and uncontrollable (ND). According to this, the ND-SBM-UO model is defined as follows:

$$
\begin{aligned}
&\tau^* = Min t - \frac{1}{m}\sum_{i\in}^{D}\frac{s_i^-}{x_{io}} \\
&s.t \quad t + \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{ro}^g} + \sum_{r=1}^{s_2}\frac{s_r^b}{y_{ro}^b}\right) = 1, \\
&\sum_{j=1}^{n}\Lambda_j x_{ij} + s_{iD}^- = t x_{io}, i \in D, \\
&\sum_{j=1}^{n}\Lambda_j z_{ij} + s_{iND}^- = t z_{io}, i \in ND, \\
&\sum_{j=1}^{n}\Lambda_j y_{rj} - s_r^g = t y_{ro}^g, r = 1,\dots,s_1, \\
&\sum_{j=1}^{n}\Lambda_j y_{rj} + s_r^b = t y_{ro}^b, r = 1,\dots,s_2, \\
&\Lambda_j \geq 0, s_{iD}^- \geq 0, s_{iND}^- \geq 0, i = 1,\dots,m, j = 1,\dots,n, \\
&s_r^g \geq 0, s_r^b \geq 0, r = 1,\dots,s, t > 0. \qquad (1)
\end{aligned}
$$

Where,

x_{ij} = ith input of jth DMU and
z_{ij} = ith uncontrollable input of jth DMU.

Note that only the controllable input excesses into the objective. A DMU is ND-SBM-UO efficient if and only if $\tau = 1$.

3.3 ND-SBM-UO and Return to Scale

To determine the returns to scale of the units with the ND-SBM-UO model, we use the model (1) in variable returns to scale mode (by adding $\sum_{j=1}^{n}\Lambda_j = t$ to the model). In the optimal solution, one of the following cases will occur:

a. If for the optimal solution of the model, there are $s_r^g \geq 0$ or $s_r^b \geq 0$. Then, to check the optimal solutions, we change $\sum_{j=1}^{n}\Lambda_j = t$ in model to $\sum_{j=1}^{n}\Lambda_j \leq t$ and solve the model. If $\tau^* = 1$, returns to scale is constant, otherwise ($\tau^* < 1$) returns to scale is increasing.

b. If for the optimal solution of the model (1), there are $s_r^g < 0$ or $s_r^b < 0$. Then, to check the optimal solutions, we change $\sum_{j=1}^{n} \Lambda_j = t$ to $\sum_{j=1}^{n} \Lambda_j \geq t$ and solve the model. If $\tau^* = 1$, returns to scale is constant, otherwise ($\tau^* < 1$) returns to scale is decreasing.

4. Empirical Study

The Adriatic Sea is strategically located between Western and Eastern Europe. The ports along its coast offer alternative trade routes and reduce dependence on other congested sea routes. The ports on the Adriatic are of great importance due to their strategic geographical position and their role in facilitating trade, transport and economic activities in the surrounding regions. They serve as vital links between Central and South-Eastern Europe and ensure maritime connectivity for the transport of goods. These ports are very important in facilitating international trade as they serve as import and export gateways. Some ports on the Adriatic coast are essential for the import and distribution of energy resources. For example, oil, natural gas and other energy-related products are imported through these ports. The Adriatic is surrounded by Italy, Slovenia, Croatia, Montenegro and Albania. In this article container terminals in these regions are evaluated. The included ports are as follows:

Port of Trieste, Italy

Situated in north-eastern Italy, the Port of Trieste represents a vital component of the Italian maritime infrastructure, boasting the highest cargo volume among the nation's ports. As a pivotal trading hub linking Central Europe with the Mediterranean, it encompasses container terminals and general cargo facilities. The port efficiently manages a diverse array of cargo, including bulk goods, Ro-Ro (Roll-on/Roll-off) shipments, and containerised freight.

Port of Venice, Italy

Located in north-eastern Italy, the Port of Venice ranks among the busiest maritime gateways in the country and holds significant importance in international trade. It accommodates a variety of cargo types, such as containers, bulk cargo, general goods, and Ro-Ro freight. Its strategic position makes it a critical logistical hub, facilitating the transportation of goods to and from northern Italy as well as other European regions.

Port of Ravenna, Italy

Positioned on Italy's eastern coastline, the Port of Ravenna plays a crucial role in the nation's maritime commerce and transport activities. The port is equipped with a range of specialised terminals designed to handle diverse cargo types. These include facilities for containers, dry and liquid bulk cargo, general goods, and Ro-Ro operations, highlighting its adaptability and capacity to support various trade requirements.

Ports of Ancona and Falconara, Italy

Situated along the central Adriatic coast, the ports of Ancona and Falconara serve as prominent maritime hubs for the region. The Port of Ancona features a comprehensive array of terminals, including those for general cargo, containers, and Ro-Ro traffic, catering to diverse shipping demands. Falconara Marittima, by contrast, is distinguished by its industrial facilities, such as oil refineries and petrochemical plants, and hosts specialised terminals for liquid bulk, including crude oil and petroleum products.

Port of Koper, Slovenia

As Slovenia's sole seaport, the Port of Koper plays an integral role in Adriatic trade and transport, serving as a gateway for Central and South-Eastern Europe. Renowned as one of the busiest ports in the region, it comprises terminals for general cargo, containers, Ro-Ro freight, and other specialised cargo types, demonstrating its strategic significance in regional commerce.

Port of Rijeka, Croatia

The Port of Rijeka, located on the northern Adriatic, is a cornerstone of maritime trade for Croatia and the broader region. Its strategic positioning enhances its role as a gateway for regional commerce. The port is outfitted with multiple terminals, including those for container handling, bulk cargo, general goods, and Ro-Ro operations, enabling it to support diverse shipping needs.

Port of Ploče, Croatia

The Port of Ploče serves as a critical maritime gateway for Croatia, significantly contributing to the nation's trade and transport activities. It is equipped with specialised terminals to accommodate various cargo types, including containers, Ro-Ro freight, and bulk goods, thereby underlining its importance in facilitating regional and international trade.

The Port of Bar, Montenegro

The Port of Bar is Montenegro's principal seaport, serving as a critical transport hub for the country. Its infrastructure includes a variety of specialised terminals capable of accommodating diverse cargo types. These terminals are designed to handle general goods, bulk and liquid bulk cargo, container shipments, and Ro-Ro (Roll-on/Roll-off) freight, highlighting its strategic importance in facilitating maritime trade and transport activities.

4.1 Data Description

After determining the target terminals of the article, the input and output indicators were defined. Determining the inputs and outputs in the process of unit performance assessment using DEA is one of the most important steps to achieve accurate results. In order to identify the key factors as inputs and outputs that lead to efficiency and inefficiency, questionnaire-based surveys and interviews with port experts and managers were conducted, and their opinions sought to ensure the reliability of the data. In addition, the sources for the emissions data were checked against official port environmental reports and the equipment levels values were checked against the inventories provided by the port authorities. This investigation was also supported by literature research. The input and output variables were selected on the basis of the key indicators identified. The data required for the port evaluation was collected from the ports. The inputs and outputs that were selected are as follow:

Total Terminal Area: The terminal area is a crucial part of a port's infrastructure, designed to the specific needs of the cargo to be handled. It is the total usable area of the container terminal, encompassing the storage area, in square meters.

Berth Length: The length of a berth is a decisive parameter for the design and operation of a port. The length of the berth contributes to the overall efficiency and capacity of a port and expresses the total size of the berth in metres.

Terminal Equipment Level: Another important indicator of port performance is a port equipment. The importance of equipment in a terminal is reflected in its role in facilitating the efficient loading and unloading, storage and transport of cargo. However, as there are some differences in the importance and function of equipment in port operations, counting of equipment and naming its number cannot show the 'value' of this indicator. For the first time in the literature, all pieces of equipment and their levels are considered in this study. Port experts provided qualitative assessments, which were converted into quantitative values using a weighted scoring method to ensure consistency and reliability between ports. The most important parts of equipment are mobile cranes, gantry cranes, reach tackers, forklifts, RMGs, RTGs, terminal trucks with trailers, tugs, rail sidings, other movers and lifters, refrigerated connections and storage capacity. The qualitative assessment was provided by experts who are familiar with the characteristics of the equipment's, differences between them, their importance and impact of their use.

Degree of Hinterland Connectivity: One of the indicators that the experts and the literature analysis have not taken into account so far, which is very important for the efficiency and performance of ports, is the connection to the hinterland. Similar to the indicator terminal equipment level, this indicator was also introduced and analysed for the first time with this study. Ports can only be successful if the development of the port goes hand in hand with the development of the connection to the hinterland. This indicator is one of the most important reasons for congestion and longer waiting times as well as for many potential problems. It was taken into account as an input in this study. A well-connected hinterland enables efficient transport of goods to and from the port. A robust transport infrastructure, including the road and rail network, facilitates the smooth transport of goods between the port and inland destinations. Well-planned hinterland connections can contribute to sustainable transport practises. Efficient logistics reduces fuel consumption and greenhouse gas emissions, thus promoting environmental sustainability.

According to the experts, road and rail connections are equally important for ports. Therefore, we first categorise all connections into two main groups, road and rail. In the road sector, we have defined 3 groups of possible connections: local roads, motorways with 2 lanes in each direction and motorways with more than 2 lanes in the same direction. In the railway sector, the port can be connected to main or other railway lines. Based on this information, the final results were announced by the experts. The container terminals were assigned a weighting according to the characteristics of the road and rail connections.

Throughput: The throughput in container terminals refers to the total volume of containers passing through the port within a given period of time. It is an important performance indicator that reflects the efficiency and capacity utilisation of a port.

Emissions: Ports and the maritime industry in general, contribute significantly to the emissions of greenhouse gas. Emissions relate to the release of various pollutants caused by operations and activities.

The main sources of emissions at container terminals are ships (engine emissions), cargo handling equipment (diesel-powered equipment, trucks and drayage vehicles) and port equipment and infrastructure. The emissions data used in this study are taken directly from the ports' environmental performance reports.

This study is based on annual data spanning (2020–2022) derived from a combination of expert interviews, official port reports and the Findaport Data Centre. The interviews were conducted with professionals actively involved in port operations and management, such as terminal managers, logistics coordinators and infrastructure planners. Quantitative data such as terminal area, water depth and berth length were crossed-checked with publicly available port statistics and information from official port websites and databases, including Findaport. The descriptive statistics of the input and output variables selected for the efficiency evaluation are shown in Table 1.

Table 1: Descriptive Statistics and Data of the Input and Output Variables.

Variable	2020			2021			2022		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Inputs									
Total Terminal Area (m^2)	48,000	427,752	224,239	48,000	427,752	224,239	48,000	427,752	224,239
Berth Length (m)	280	4,612	1,867	280	4,612	1,867	280	4,612	1,867
Water Depth (m)	10.5	17.9	12.975	10.5	17.9	12.975	10.5	17.9	12.975
Terminal Equipment Level	70	90	80	70	90	80	70	90	80
Degree of Hinterland Connectivity	40	180	107	40	180	107	40	180	107
Outputs									
Throughput (TEU) (Desirable)	25,717	945,051	344,929	21,526	997,574	353,199	21,729	1,017,788	397,461
Emissions (tCO_2eq) (Undesirable)	1,395.3	21,793.8	8,246.8	857.2	22,234.2	8,133.1	851.6	25,455.1	9,278.1

4.2 Results

In this article, the sustainability-based efficiency of the above-mentioned container terminals on the Adriatic Sea is evaluated based on the indicators described in 4.1, which are the most important from the perspective of port specialists, as well as on the basis of limitations. In this study, Lingo software was used to calculate and analyse the efficiency of the Adriatic container terminals from 2020 to 2022.

The input depth of water is uncontrollable, as the water depth is not directly under the control of the DMUs. This input represents an external constraint that affects the performance of container terminal but cannot be controlled or influenced by it. For this reason, the model proposed in this article is defined with the aim of keeping this variable constant. Thus, the purpose of the proposed model is to evaluate the container terminals in the presence of an uncontrollable input. That is, the objective is to reduce the input and increase the output. With the exception of the desired input. Table 2 presents the sustainability-based efficiency scores for container terminals, where a score of 1 indicates efficiency, and scores below 1 signify inefficiency.

Table 2: Results of Sustainability-Based Efficiency using the ND-SBM-UO Model.

Ports	2020		2021		2022		Return to Scale
Port of Koper	1	Efficient	1	Efficient	1	Efficient	CRS
Port of Trieste and Monfalcone	1	Efficient	0.77982	2	1	Efficient	CRS
Port of Venice and Falconara	0.68247	4	0.66694	4	0.74095	4	IRS
Port of Ravenna	0.52471	6	0.61841	6	0.60127	6	IRS
Port of Ancona	0.62448	5	0.64653	5	0.60543	5	IRS
Port of Rijeka	0.74765	3	0.73549	3	1	Efficient	CRS
Port of Ploce	0.14675	8	0.14131	8	0.14223	8	IRS
Port of Bar	0.23589	7	0.21069	7	0.20403	7	IRS

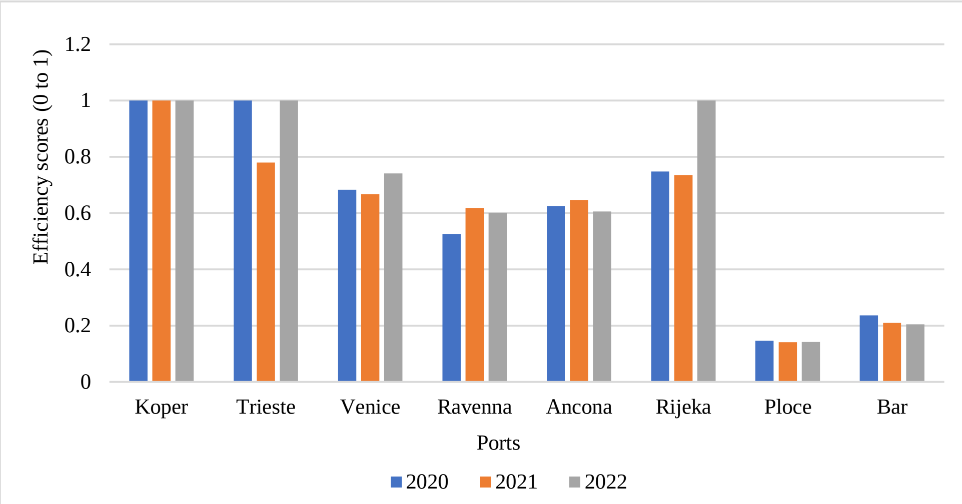

Figure 2: Efficiency Scores of 8 Container Terminals (DMUs) in the Adriatic from 2020 to 2022

An analysis of ND-SBM-UO efficiency scores for individual container terminals shows that in 2020, only three terminals achieved full efficiency, with a score of 1: the container terminals at the ports of Koper, Trieste and Monfalcone, and Rijeka, which is 25% of the total terminals. The rest of the terminals were inefficient by scoring below 1. In 2021, full efficiencies has been attained by the container terminal at the Port of Koper, which covered 12% of the total ports while the rest still remained inefficient. In 2022, the same three terminals as in 2020 were efficient and, in total covered 37%. The findings indicates that the COVID-19 pandemic disrupted the port operations across the region in 2020 and 2021. The average operational turnaround times recovered during 2022. The average efficiency scores of container terminals for 2020, 2021, and 2022 were 0.61774, 0.59989, and 0.66174, respectively.

The Port of Koper was the most efficient container terminal in the region for all three years. Its strategic position as a transhipment hub connecting Asia, Europe, and other continents, coupled with its favourable location along major shipping routes and good connectivity to inland rail and road networks, is the basis of its high performance.

Effective management practices have further enhanced its efficiency. Container handling remains the main activity at the Port of Koper, as containers accounted for more than 67% of the port's total cargo throughput in 2020 and 2021, and 61% in 2022. The container terminal of the port of Trieste is efficient in 2020 and 2022 and inefficient in 2021 due to a decrease in cargo volumes, which may have been affected by the problems caused by the pandemic, but is in second place. The port is an important centre for international trade due to its proximity to major European markets, including Austria, Hungary, the Czech Republic and Slovakia. This shows that the port of Trieste plays an important role in economic growth and industrial development in the region. It also indicates good port management. However, container handling accounts for 19, 18 and 20% of the port's total cargo.

The container terminal of the port of Rijeka achieves generally acceptable results in the region. In 2020 and 2021 it is not efficient, but was relegated to third place, but in 2022 it is efficient. This may be due to the 22% increase in container traffic and good communication with international partners, shipping companies, logistics providers and government organisations. It is also due to the strategic partnerships of the port's position as a leading maritime gateway in the Adriatic region. But this is not true for the port of Ploce that has the lowest efficiency scores in the analysed year with 0.14675, 0.14131 and 0.14223. This is due to the following reasons: this port has limited infrastructure and facilities compared to other major ports in the region, which can be a reason for its limited ability to deal with cargo volumes that are constantly increasing and its ability to accept larger vessels. Emissions in this port are higher than in other units. The port requires significant investment in modernising infrastructure, improving technology and expanding capacity to remain competitive and meet the evolving needs of the maritime industry. About 10% of the port's cargo throughput in 2020 is accounted for by the container terminal and in 2021 and 2022 it will be about 7% and 5% respectively, showing the decline in the container terminal's operational performance.

The container terminal at the port of Bar also has a low efficiency rating and faces with the limited infrastructure and consequent limited ability to accept larger vessels and to handle increasing cargo. Connectivity to domestic transport systems such as the rail and road networks are inadequate or inefficient, which affects the port's ability to serve as an efficient logistical gateway for the region. In 2020 and 2021, this terminal account for 31% and 33% of the port's total cargo volume respectively, but in 2022, container throughput decreases by more than 10% and the share of the port's total cargo volume will be about 19%. In fourth place is the container terminal of the port of Venice, where container throughput accounts for around 30% of total port throughput, and fifth place is the port of Ancona and Falconara, where container throughput accounts for around 10% of port throughput.

This study identifies the scale efficiency of the units as decreasing (DRS), increasing (IRS), or constant returns to scale (CRS) based on the proposed method. Table 2 shows that all the inefficient container terminals have IRS, while the three efficient ones have CRS. Terminals with IRS can significantly improve their efficiency by scaling up their operations to match the efficiency of their reference terminals.

Table 3 shows the reference set of DMUs. Efficient container terminals can be a reference set and a good benchmarking tool for inefficient container terminals. The reference sets provide an inefficient container terminal with information on which container terminal(s) it needs to imitate in order to be efficient. The inefficient container terminals can orient themselves on their efficient reference container terminals in order to improve and become more efficient. This benchmarking process enables inefficient ports to gain insights into best practices, reduce inefficiencies and improve their output by optimizing input use based on the performance of efficient ports. The container terminal at the Port of Koper is the most commonly used benchmark for inefficient terminals, while the terminal at the Port of Trieste is a benchmark for two others. This benchmarking analysis will help inefficient terminals improve efficiency by optimizing controllable inputs to attain desirable outputs (TEU).

Table 3: Reference Sets and Return to Scale

No	Ports	Reference Sets		
		2020	2021	2022
D1	Port of Koper	D1	D1	D1
D2	Port of Trieste and Monfalcone	D2	D1	D2
D3	Port of Venice and Falconara	D1	D1	D1, D2
D4	Port of Ravenna	D1	D1	D1, D2
D5	Port of Ancona	D1	D1	D1
D6	Port of Rijeka	D1	D1	D6
D7	Port of Ploce	D1	D1	D1
D8	Port of Bar	D1	D1	D1

The results of this study, as shown in Fig. 3, indicates that larger TEU volumes is not necessarily correlate with higher efficiency. For example, the container terminal at the Port of Venice is less efficient despite its larger size compared to the Port of Rijeka. On the other hand, the container terminal at the Port of Ancona is more efficient than that at the Port of Ravenna, which is smaller in size. These findings reveal that higher throughput does not always mean greater efficiency.

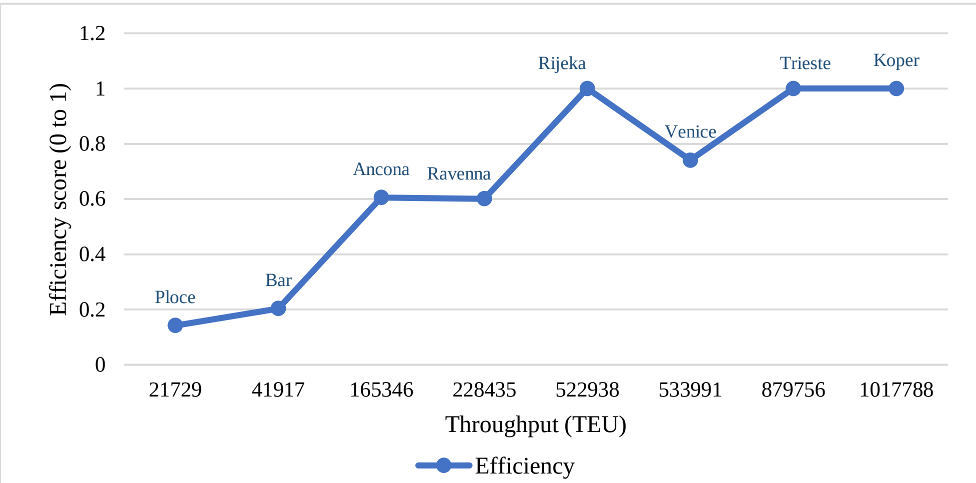

Figure 3: Relationship between Efficiency and Throughput.

From the analysis of the relationship between efficiency and the size of the container terminal area, the obtained results suggest that not always large container terminals are more efficient than the smaller one (see Fig 4). For example, the container terminal in the port of Koper is smaller than those at the port of Ravenna, Venice and Trieste but more efficient. The port of Rijeka has a container terminal that is smaller than the above ports but more efficient.

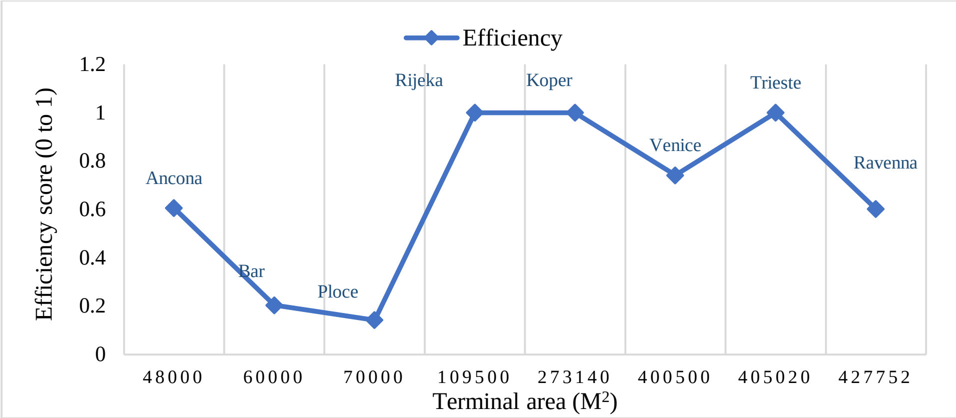

Figure 4: Relationship between Efficiency and the Size of the Container Terminal Area.

Given the optimal input-output ratio, the inefficient ports are doing what they need to do to reach the efficiency frontier. In terms of input management, the Port of Venice, for example, should either reduce the size of its container terminal or change the length of the berth while keeping the same size. If it prefers to leave the input criteria unchanged, it must increase cargo throughput. In line with this increase, measures should also be taken to reduce emissions in order to reduce undesirable output. In addition, the port should consider its reference port as a model to learn from. Other inefficient ports should adopt a similar approach to input and output. In general, this can be difficult for these ports. But to be efficient, they must have appropriate measures in place.

5. Discussion

This study examines the sustainability-driven efficiency of container ports in the Adriatic region to gain insight into the operational strength and weakness profiles of key terminals. Using a newly developed ND-SBM-UO model, we analysed eight container terminals in the region. The efficiency scores are important for port management as they prompt them to address deficits and problems in the ports. Therefore, the application of DEA proves to be helpful in identifying the least efficient container terminals that need to be given the highest attention.

Container terminals' efficiencies at the eight ports of the Adriatic reveal some quite uneven distribution; that is, while only three appear to be close to being truly optimal. Of the container terminals of 8 ports in the Adriatic region, only 3 are considered efficient; the remaining container terminals are inefficient. In particular, the container terminal in the Port of Ploce has the lowest level of efficiency. It is noteworthy that all inefficient terminals of ports in the region show increasing returns to scale, indicating that these container terminals need to improve their operational capabilities, such as hinterland connectivity and equipment, in order to reach the efficiency of their reference container terminals. The results of the study illustrate that factor such as container terminal size alone does not determine efficiency or inefficiency, as shown by the fact that some smaller container terminals outperform the larger container terminals in terms of return on investment. This evidence further highlights the need to upgrade operational capabilities, including connectivity and equipment, in order to enhance the productivity of the inefficient terminals and gain more ground over their efficient counterparts.

Looking at the results of the performance assessment, only a few container terminals have reached their performance limit for the entire 2020-2022 period. The impact of the Covid-19 pandemic on the ports is obvious: the total volume of container traffic in the Adriatic ports has reached more than 2,825,594 TEU in 2021, an increase of only one percent compared to 2020. But the total volume of transport in 2022 has reached more than 3179691 TEU, which means an increase of about 354097 TEU. In particular, the volume of container transport in the region has increased compared to 2020. Ultimately, the findings underline the challenges and growth opportunities remaining for the Adriatic container port sector, reiterating the necessity of targeted efficiency improvements to be maintained in the years ahead.

Also considering that this assessment is based on sustainability. Taking into account the results of this study, the total emissions in the container terminals of the Adriatic ports amounted to 65,996.8 tonnes in 2020, which has reached 65,690.8 tonnes in 2021 and 74,224.8 tonnes in 2022. This shows that emissions are increasing at the same time as the increase in cargo volumes. Inefficient ports can consider the following strategies:

Ports with excessive input variables, such as terminal size or berth length, should balance these inputs with their operational needs. For example, Venice may consider resizing its terminal or increasing throughput to improve its input-output ratio.

The reference sets in this study provide a clear benchmarking tool. Inefficient ports such as Ploce and Bar should emulate the practices of efficient ports such as Koper and Trieste, which are characterised by management, connectivity and strategic partnerships.

Improving hinterland connectivity through rail and road development can significantly increase operational efficiency. Ports such as Ploce and Bar can benefit from targeted investments in technology and handling equipment.

With these strategies, inefficient ports can reduce their deficits and move closer to the efficiency frontier. The results of this study emphasize the importance of balancing growth and sustainability.

6. Conclusion

Port operators should consider investing in infrastructure, increasing throughput capacity and reducing emissions to optimise performance. The port of Venice and port of Ravenna need to expand by changing the size of their container terminal area or berth while maintaining the same performance. It is important to note that due to limited access to certain data, factors such as financial metrics (e.g., costs, profit, and labour) were not included in this study. Although the exclusion of financial metrics may limit the overall assessment of efficiency, future studies could include financial data to provide a more complete assessment of port performance. The inclusion of financial indicators such as operating costs and revenues would help to provide a clearer picture of how economic factors influence efficiency. In addition, further studies could explore the dynamic interplay between financial metrics and sustainability factors such as emissions, which were emphasized in this study. Despite these limitations, this study has broadened our understanding by identifying key factors that contribute to efficiency, even in the absence of comprehensive data. Therefore, this study emphasizes the importance of using DEA to identify accurate indicators for assessing efficiency of DMUs.

7. Study Limitations

While this study provides insightful information on the sustainability-driven efficiency of container ports in the Adriatic region using the ND-SBM-UO model, there are a few limitations that could have an influence on the findings. One of the major limitations is the lack of access to some financial data, including operating costs, revenues, and labour statistics. These are some of the metrics that would have helped understand the economic side of port performance, but they were not included in this analysis. Without them, the study cannot fully explore the financial drivers behind efficiency or the broader economic impact of operational decisions. Another limitation is that the study based its analysis on sustainability and operational efficiency. These are essential dimensions of any port operation; however, economic policies, trade patterns, or global market dynamics are critical aspects that were not addressed. These factors can significantly influence the performance of the ports, and their absence may make the analysis less accurate.

The scope of this geographical research is a bit narrow in terms of concentrating only on the Adriatic region. With this focus, one can dive deep into specifics but not make findings as directly applicable to other regions' ports, which face totally different issues or operate in a completely different environment. Therefore, by increasing the scope of research in further studies, one may make it more generally relevant. It further relies on cross-sectional data that only provides a snapshot of efficiency at a given point in time. This type of approach cannot track changes or trends over the years. Longitudinal study could provide insight into how the efficiency evolves over time, particularly as sustainability initiatives and operational practices develop. Lastly, while the ND-SBM-UO model is robust, it has some limitations. It does capture undesirable outputs like emissions pretty well but oversimplifies the interaction between multiple factors. Hybrid models that combine analytical approaches, for example, through machine learning or stochastic analysis, can provide a far more detailed efficiency understanding.

8. Implications

Implications of this study to both port operators and policy makers are numerous. First, port operators need to focus on their improved operational capabilities, including better infrastructure, better hinterland connectivity, and more recent equipment reforms especially in inefficient ports. This leads to results that demonstrate how some of the container terminals along the Adriatic are efficient in spite of being smaller than the others. Thus, expansion becomes less critical and more optimal when current operations are optimized first. For the policy makers, strategic investments need to be carried out in line with the total efficiency of ports; for example, environmental sustainability is improved. Increasing emissions and increasing cargo volumes indicate that port authorities should adopt sustainable practices to balance growth with environmental responsibility. This can be incentives for green technologies, better waste management, and energy-efficient equipment. Encouraging collaboration between ports and industry leaders to share best practices and optimize the use of resources can also be part of policy considerations.

9. Future Research Directions

Further studies can expand upon this study by including more variables, such as financial metrics-costs, revenue, and labour-to provide a more holistic perspective of port performance. These would include the critical inputs for the financial underpinnings of terminal operations that allow researchers and practitioners to examine the impact of economic inputs on efficiency outcomes. Examining how these financial factors interact with operational measures could uncover nuanced drivers of performance, shedding light on the allocation of resources and their impact on terminal productivity. This also would be meaningful when it suggests further specific relationships between economic factors and sustainability indicators like greenhouse gas emissions, from which a more improved understanding of the whole sustainable port management activity could be derived. For example, further research could examine how changes in operational cost or labour efficiency relate to changes in emissions, providing insight into where there may be trade-offs or synergies between economic performance and environmental impact. Future research could also include temporal and regional dimensions that would be highly informative. Longitudinal analysis may indicate efficiency improvement or decline over time, while cross-region comparison may help draw attention to context-specific factors driving terminal performance. For example, regional differences in energy prices, labour costs, or regulatory conditions may condition the relationship between financial metrics and sustainability indicators.

Further inquiry into financial as well as environmental implications may reveal how technology is responsible for operational improvements without adding to energy usage and emissions. Finally, future studies could adopt hybrid analytical models that combine DEA with other advanced methodologies such as stochastic frontier analysis or machine learning techniques to make evaluations of container terminal efficiency more robust and precise. In addition, such models could be used for the applicability of a larger set of variables that include weather conditions, congestion levels, and customer satisfaction. These areas may be addressed to contribute toward future research, with the potential of holistic strategies in increasing terminal efficiency and balancing economic goals with sustainability objectives while developing more resilient and environmentally conscious port operations.

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