JOURNAL OF MARITIME RESEARCH

Vol XXI. MT24 (2024) pp 19–23

ISSN: 1697-4840, www.jmr.unican.es

Ranking of Adriatic Sea Container Ports Using DEA

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ARTICLE INFO

Article history:
Received 15 Jul 2024;
in revised from 24 Jul 2023;
accepted 16 Aug 2024.

Keywords:
Adriatic ports efficiency, Data envelopment Analysis (DEA), Cross-efficiency, Undesirable output.

ABSTRACT

Ports are important transport hubs and facilitate the movement of goods for businesses in local communities and global markets. Ports on the Adriatic Sea play a special role in European transport due to their shorter distance to Asian and African markets. The ranking of ports is important not only to assess their efficiency, but also to create a competitive environment and enable port managers and policy makers to recognize and take into account their strengths and weaknesses, leading to an improvement in the performance of ports in general. Data Envelopment Analysis (DEA) is a non-parametric method for evaluating and ranking entities. Cross-efficiency is one of the ranking methods that is able to evaluate all decision-making units (DMU), including efficient and inefficient units. This method has been developed in this article for the presence of uncontrollable inputs and undesirable outputs in an uncertain environment. Therefore, the article deals with the ranking of Adriatic container ports from an economic and environmental perspective using the new improved cross-efficiency method.

1. Introduction.

Ports play a multifaceted role in global trade, transport and economic development. Their importance goes beyond maritime logistics and influences regional development, supply chain dynamics and national and international trade policy. Ports are very important hubs for global trade and facilitate the movement of goods between countries and continents. Therefore, port rankings provide information about their efficiency, infrastructure and competitiveness in the transport of seaborne goods. Ports that rank higher in terms of efficiency and infrastructure are more attractive to shippers and companies and increase their competitiveness on the global market. Port rankings also help companies and logistics providers to find efficient transport routes.

Ports with better rankings are often associated with better infrastructure, streamlined processes and faster turnaround times, leading to improved supply chain efficiency. Governments and port authorities can use port rankings as a benchmark for prioritizing investment and allocating resources to port development projects.

In the presence of environmental factors, ports that prioritize environmental sustainability can receive a higher score, reflecting their commitment to reducing pollution and promoting sustainable maritime practices.

Due to their strategic location, modern infrastructure and the fact that they are the gateway to Europe for goods from Asia, the Middle East and other regions, Adriatic ports are important players in the maritime industry, supporting and strengthening trade flows and economic growth in the Adriatic region [1, 2]. Due to the particular importance of these ports, their ranking serves as a valuable tool for maritime industry stakeholders, including investors, policy makers and port authorities. The port ranking provides insights into the performance, competitiveness and sustainability of ports and improves infrastructure, operations and regulatory frameworks to support global trade and economic growth.

Data envelopment analysis is the best method for evaluating the efficiency and ranking of units because it is a non-parametric method that takes into account most performance criteria and involves multiple inputs and outputs [3]. This pa-

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per presents the performance evaluation of ports using the DEA method. The main objective is to evaluate the efficiency and rank them when there are undesirable outputs. In this research, we use a cross-efficiency method based on non-classical DEA model (Slacks-based Model (SBM-UO)) to rank ports. Also, an improved DEA model is developed in the presence of uncontrollable indicators. The proposed cross-efficiency model for the case of constant returns to scale case is discussed. Based onthe results of the ranking, ports can make positive changes, attract more investments and strengthen their position in the maritime industry.

The paper is organised as follows. Section 2 provides a general overview of the literature on previous studies. The proposed DEA methodology is presented in Section 3. Section 4 applies the proposed framework to the ranking of Adriatic ports in an empirical case. Finally, the discussion and conclusion are drawn in Section 5.

2. Literature Review.

Studies on port analysis from an economic point of view, based on the DEA, date back to 1993. Rolle and Hayuth were the first to use DEA to access the efficiency of ports. They showed that DEA efficiency assessment can be a useful tool for port managers and researchers, providing a deeper insight into port performance [4].

For the first time, the environmental efficiency of ports in East Asian ports was evaluated [5]. Chin et al. (2010) identified negative externalities in the production of port services in East Asia by explicitly considering the environmental impacts of shipping using CCR, BCC and SBM models [5].

Several articles have addressed the issue of port ranking. Lee et al (2005) applied a new DEA based method called RDEA (Recursive DEA) to produce a ranking of selected container ports in the Asia-Pacific region. The article compared the DEA and RDEA rankings of the ports and analysed the result to identify tactical measures to improve efficiency [6]. Cullinane et al (2005) evaluated the efficiency of the world's largest container ports and terminals using two alternative techniques, DEA and the FDH model. The results provide an insight into the current efficiency ranking of the world's largest container ports and terminals. In turn, they presented the advantages and disadvantages of port privatization and provided an empirical investigation of the relationship between privatization and relative efficiency in the container port industry [7]. Wu et al (2010) showed that DEA is used as an effective tool to evaluate the relative efficiency for measuring the performance and benchmarking of the 77 global container ports in 2007. The results for the efficiency scores are analysed and a clear ranking of the ports based on the average cross-efficiency is established [8]. Pjevčević et al. (2011) used the DEA method to evaluate the efficiency of the proposed alternatives and show their ranking based on simulation results [9]. Niavis et al (2012) investigated the benchmarking, measurement and identification of the key determinants of technical efficiency of container ports in the South East Europe region, including Italian ports [10]. Munim (2020) applied the DEA and Free Disposal Hull (FDH) methods to evaluate and rank the efficiency of 38 container terminals from 17 different ports in 12 Asian countries [11]. Iyer and Nanyam (2021) analysed the efficiency of Indian container terminals and classified them into high and low performing terminals. Their findings recommend port managers to improve the efficiency of existing terminals and increase the scale of operations [12]. To summaries, there are a few performance evaluation methods, with DEA being the most preferred method by evaluators due to its effectiveness in performance evaluation [13]. Current methods ignore some limitations of DEA models in evaluation. For this reason, the efficiency scores are not accurate enough to be used for port performance improvement and they are generally not useful for port users. There is also no study in the literature on the ranking of ports in the Adriatic region.

3. Research Methodology.

In order to rank the Adriatic ports, this study proposes an improved DEA approach. After defining the purpose of the study, the input and output variables are determined. Then, the improved cross-efficiency based on the SBM-UO method is used to rank the Adriatic ports. Finally, the research results for the Adriatic ports are analysed and discussed.

3.1. SBM model and cross-efficiency.

We assume that there are n DMUs to be evaluated with m inputs and s outputs. x_{ij} , $(i = 1, ..., m)$and y_{rj} , $(r = 1, ..., s)$denote the input and output values of DMU_j which are all known and non-negative.

SBM efficiency is proposed to evaluate efficiency with slack values. Following the concept of the efficient production frontier, the SBM model is defined as follows [14]:

$$\begin{aligned}
&\rho = Min \quad \frac{1-\frac{1}{m}\sum_{i=1}^{m} s_i^-/x_{io}}{1+\frac{1}{s}\sum_{r=1}^{s} s_r^+/y_{ro}} \\
&\text{s.t} \quad \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = x_{io},\ i = 1, ..., m, \\
&\quad \sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{ro},\ r = 1, ..., s, \\
&\quad \lambda_j \geq 0,\ j = 1, ..., n,\ s_i^- \geq 0,\ i = 1, ..., m, \\
&\quad s_r^+ \geq 0,\ r = 1, ..., s.
\end{aligned} \tag{1}$$

In model (1), $\rho$is the SBM efficiency of $\text{DMU}_o.s_i^-$, $i = 1, ..., m$ and s_r^+, $r = 1, ..., s$ are called slacks. If$x_{io} = 0$, then the term $s_i^-/x_{io}$is eliminated. If$y_{ro} = 0$, then it is replaced by a very small number so that the term s_r^+/y_{ro} has a compensatory effect.

The SBM model is a non-radial performance evaluation model. In non-radial models, the efficiency value of the decision units is determined in addition to the efficiency measurement. The difference between the SBM model and other DEA models is that the model is based on slacks variables; for this reason, it shows more accurate results. It proves that efficiency evaluation with the SBM model can avoid the angular and radial defects of the traditional DEA model and improve the accuracy and reliability of efficiency evaluation.

In DEA, each DMU selects the most favourable multipliers to measure efficiency, and different DMUs often use different multipliers. This makes the efficiency scores of the DMUs incomparable. To make them comparable and rank them, it is essential to calculate the cross-efficiencies. The idea is to use the multipliers chosen by each DMU to calculate the efficiency of all other DMUs.

Let ρ_{ok} be the efficiency of DMU_k calculated from the multipliers selected by DMU_o through the input model. Then the efficiency of DMU_k using the multipliers selected by DMU_o is given by [15]:

$$\rho_{ok}=\frac{1-\frac{1}{m}\sum_{i=1}^{m} s_i^{-*}/x_{ik}}{1+\frac{1}{s}\sum_{r=1}^{s} s_r^{+*}/y_{rk}}, \quad k=1,...,n \tag{2}$$

where "*" denotes optimal values solved from model (2). This process is repeated by using the multipliers that each DMU_o has chosen when calculating its efficiency to calculate the efficiencies of all DMUs. The final efficiency of DMU_k is the average of ρ_{ok}, $o = 1, ..., n$:

$$\rho_k = \frac{1}{n}\sum_{o=1}^{n}\rho_{ok} \tag{3}$$

To solve Model (1), it can be converted into the following linear programming model [14]:

$$\begin{aligned} &\rho = Min \quad \tau = t - \tfrac{1}{m}\sum_{i=1}^{m} s_i^-/x_{io} \\ &s.t \quad \sum_{j=1}^{n}\mu_j x_{ij} + s_i^- = t x_{io},\ i=1,...,m, \\ &\quad \sum_{j=1}^{n}\mu_j y_{rj} - s_r^+ = t y_{ro},\ r=1,...,s, \\ &\quad 1 = t + \tfrac{1}{s}\sum_{r=1}^{s} s_r^+/y_{ro}, \\ &\quad \mu_j \ge 0,\ j=1,...,n,\ s_i^- \ge 0,\ i=1,...,m, \\ &\quad s_r^+ \ge 0,\ r=1,...,s,\ t>0. \end{aligned} \tag{4}$$

3.2. Improved SBM-UO model and cross-efficiency.

In this section, model (4) is developed despite the undesirable outputs and uncontrollable inputs. Assume that the input variables can be divided into two subsets, namely controllable (D) and uncontrollable (ND). The outputs are divided into desirable $y_{ro}^g (r=1,...,s_1)$ and undesirable $y_{ro}^b (r=1,...,s_2)$. According to this distinction, the ND-SBM-UO model is shown in Eq.(5).

$$\begin{aligned} &\tau^* = Min \quad t - \tfrac{1}{m}\sum_{i\in}^{D}\tfrac{s_i^-}{x_{io}} \\ &s.t \quad t + \tfrac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\tfrac{s_r^g}{y_{ro}^g} + \sum_{r=1}^{s_2}\tfrac{s_r^b}{y_{ro}^b}\right) = 1, \\ &\quad \sum_{j=1}^{n}\Lambda_j x_{ij} + s_{iD}^- = t x_{io},\ i\in D, \\ &\quad \sum_{j=1}^{n}\Lambda_j z_{ij} + s_{iND}^- = t z_{io},\ i\in ND, \\ &\quad \sum_{j=1}^{n}\Lambda_j y_{rj} - s_r^g = t y_{ro}^g,\ r=1,...,s_1, \\ &\quad \sum_{j=1}^{n}\Lambda_j y_{rj} + s_r^b = t y_{ro}^b,\ r=1,...,s_2, \\ &\quad \Lambda_j \ge 0,\ s_{iD}^- \ge 0,\ s_{iND}^- \ge 0,\ i=1,...,m,\ j=1,...,n, \\ &\quad s_r^g \ge 0,\ s_r^b \ge 0,\ r=1,...,s,\ t>0. \end{aligned} \tag{5}$$

with
x_{ij} = ith input of jth DMU,
z_{ij} = ith uncontrollable input of jth DMU,
s_r^g = slack variable of desirable output and
s_r^b = slack variable of undesirable output.

A DMU is ND-SBM-UO efficient if and only if $\tau = 1$. If τ is the optimal solution of the model (5), then the efficiency of the DMU_k using the multipliers selected by DMU_o is as follows:

$$\tau_{ok}=\frac{1-\frac{1}{m}\sum_{i\in D} s_{iD}^{-*}/x_{ik}}{1+\frac{1}{s_1}\sum_{r=1}^{s_1} s_r^{g*}/y_{rk}+\frac{1}{s_2}\sum_{r=1}^{s_2} s_r^{b*}/y_{rk}}, \quad k=1,...,n \tag{6}$$

The final cross-efficiency of DMU_k is the average of τ_{ok}, $o = 1, ..., n$,

$$\tau_k = \frac{1}{n}\sum_{o=1}^{n}\tau_{ok} \tag{7}$$

4. Empirical Study.

In this section, we have ranked Adriatic container ports using the proposed cross-efficiency method. The data is taken from the ports' websites [16]. The analysis of these ports can reflect the development status of the ports.

4.1. Inputs and outputs selection.

This study measures the performance efficiency of 8 container ports, including 4 Italian ports (Trieste, Venice, Ravenna and Ancona), two port in Croatia (Rijeka and Ploce), one Slovenian port (Koper) and one port in Montenegro (Bar) in 2021. The inputs and outputs were determined on the basis of the results of the literature research and availability. The inputs and outputs are described below.

Input indicators

Water depth: Water depth refers to the depth of water, in metres, into which a vessel will be submerged when fully loaded.

Berth length: This factor refers to the total size of the berth at the terminal under study, expressed in metres.

Total terminal area: This is the total usable area of the terminal, including the storage area, measured in square metres.

Level of equipment: The equipment provided includes gantry cranes, mobile cranes, RMGs, RTGs, reach stackers, forklifts, terminal trucks with trailers, railway sidings, tugs, other mover and lifters, storage capacity and refrigerated connections. Experts familiar with the characteristics, importance and differences of this equipment assigned numerical values to the qualitative characteristics based on their importance and impact.

Output indicators:

Throughput: Throughput is the total volume of containers handled annually, measured in tonnes.

Emissions: The maritime industry, including ports, contributes significantly to greenhouse gas emissions. Emissions from container ports refer to the release of various pollutants as a result of the operations and activities carried out at container terminals.

The descriptive statistics of the input and output variables were selected for the assessment and the ranking is shown in Table 1.

Table 1: Descriptive statistics of the input and output variables.

Variables	Min	Max	Mean
Total terminal area (m2)	48,000	427,752	224,239
Berth length (m)	280	4,612	1,867
Water depth (m)	10.5	17.9	12.975
Level of equipment	70	90	80
Throughput (TEU) (desirable)	21,526	997,574	353,199
Emissions (tCO2eq) (undesirable)	857.2	22,234.2	8,133.1

Source: Authors.

4.2. Container ports ranking by proposed method.

One of the inputs (Water depth) is uncontrollable, as water depth is a factor that is not directly under the control of the DMUs being assessed. The second output, Emissions, is an undesirable output.

Table 2: Ports efficiency and cross-efficiency scores.

Ports	Efficiency score	Cross-efficiency	Ranks
Port of Koper	1	1	1
Port of Trieste	0.77982	0.56435	2
Port of Venice	0.66694	0.47673	4
Port of Ravenna	0.61841	0.39951	6
Port of Ancona	0.64653	0.42723	5
Port of Rijeka	0.73549	0.51676	3
Port of Ploce	0.14131	0.08459	8
Port of Bar	0.21069	0.12438	7

Source: Authors.

Table 2 shows the efficiency and cross-efficiency scores estimated for the ports using model (5) and (6). An efficiency score of 1 indicates efficient ports and scores below 1 indicate inefficient ports. The remaining terminals are inefficient, with scores below 1. The results of the ranking of regional ports using cross-efficiency scores are shown in the last column of Table 2. Fig. 2 shows the efficiency scores of 8 ports.

5. Discussion and Conclusion.

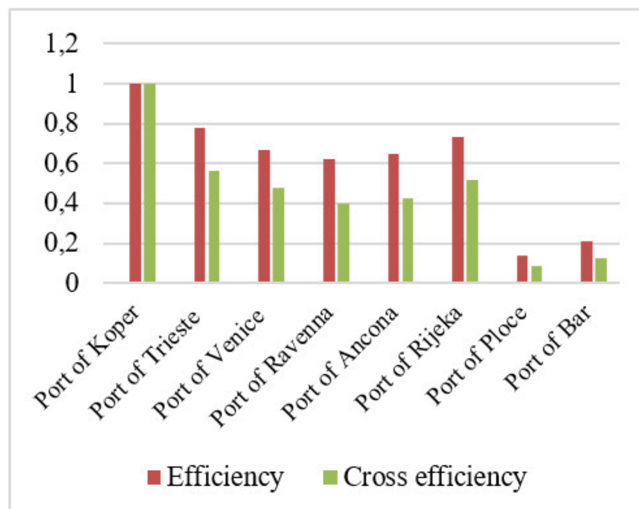
The analysis shows that only the port of Koper is efficient. The other terminals are inefficient. The average efficiency score of the ports in is 0.59989.

Also in terms of cross-efficiency, only the port of Koper is efficient and the other ports are inefficient. Figure 1 shows the differences in the efficiency and cross-efficiency scores.

In general, the cross-efficiency values based on the new proposed model are not high. This shows that there is still much to improve in the development of ports.

One of the reasons is ports geographical advantages. It is worth noting that the port of Rijeka is not very large, while its efficiency is relatively high. In contrast, the length of the terminal in the port of Venice and the cargo capacity are larger and have a lower score. Although the dimensions of the cargo capacity are closely related to efficiency and sustainability, they are not proportional.

Figure 1: Cross-efficiency and efficiency scores.



Source: Authors.

The results also show that the port of Koper received the best efficiency score, followed by the port of Trieste and port of Rijeka. The ports of Venice and Ancona are also in the next ranks. The port of Ploce has a worse result among the ports assessed.

Compared to other larger ports in the region, the port of Ploce has limited infrastructure and facilities, which may limit its ability to handle increasing cargo volumes and accommodate larger vessels. Pollution levels in this port are higher than in other ports under study. Therefore, more investment is needed to improve infrastructure and expand capacity.

Considering that cross-efficiency expands the concept of efficiency by looking at the performance of each DMU relative to others in the dataset, rather than comparing it to its own performance. It also looks at the relative performance of all DMUs simultaneously, rather than evaluating each DMU individually. Therefore, cross-efficiency scores provide a more comprehensive assessment of each DMU's performance by considering its relative performance compared to other DMUs in the dataset.

Cross-efficiency measures the performance of a DMU compared to all other DMUs in the dataset. It can therefore be said that by considering the relative efficiency of each DMU in different dimensions, cross-efficiency provides a broader perspective on performance and becomes a useful tool for ranking and identifying the best performers.

This study has limitations in terms of input and output indicators. Other variables such as labour should be included in this study to understand their impact. The impact of financial factors can also be investigated. The future scope can include analyses that can impact operational and financial efficiency. Therefore, in the future, this study can be extended to understand the profitability and sustainability of container terminals when the required financial data is available.

Acknowledgements.

This article was supported by the Slovenian Research and Innovation Agency under Public Call for the (co-) financing of Marie Skłodowska-Curie – Seal of Excellence research projects, grant number N1-0287.

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