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Global Ports Efficiency and Productivity Using DEA-MPI Approach

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Abstract

Ports are crucial to the economy of many nations; thus, numerous studies have been conducted on port efficiency and productivity. This study analyses the efficiency and productivity of some major global ports namely, Port of Singapore, Rotterdam, Antwerp and Durban. The main objectives of this study are to determine the level of operational efficiency of the mentioned ports, measure and evaluate the ports' productivity changes and lastly to investigate the factors influencing the productivity changes of the ports studied. To achieve these objectives, Data Envelopment Analysis (DEA-BCC) model was used to determine the technical and operational efficiencies of the ports and Malmquist productivity index was employed to calculate the various productivity levels. The results of the study can guide stakeholders to formulate their operational strategies for port efficiency and productivity. The study also has policy suggestions that are uniquely targeted to Africa's issues and potential.

Keywords

Efficiency, Productivity, Data Envelopment Analysis, Malmquist Productivity Index

1. Introduction

Ports are points of intersection between land and maritime space, an intermodal place of convergence, and a knot where inland and maritime transport lines meet [1]. Global trade has been steadily growing since the turn of the twenty-first century, and this has led to significant changes in the worldwide transportation system and, therefore, a radical shift in global logistics [2]. Ports are essential to a nation's economy and growth since they serve as a conduit for international trade, hence their effectiveness is crucial [3]. Major ports like Rotterdam, Antwerp, Durban, and Singapore support about 80% of global commerce by volume [4]. These ports are significant hubs for innovation and economic activity, not only places to transit. The most important aspect of ports is for them to be efficient and productive to a certain degree with regards to their available resources. Research on port efficiency and productivity has gone far back, but it is still mostly relevant in modern times as it affects the several marine sector players [5]-[9].

The maritime shipping industry is undergoing significant technological advancements that have an impact on the need for port infrastructure and services [10]. The most visible one is the growing containerization of international trade, a trend that is anticipated to last for some time. Ports play an indispensable role in national economies, serving as gateways for international trade, facilitators of industrial growth, and drivers of regional and national development. The ports discussed Durban, Singapore, Antwerp, and Rotterdam offer exemplary case studies on how modern ports contribute significantly to economic prosperity. Each port has developed unique attributes that underpin its contribution to its nation's economy, reflecting broader trends in the global maritime industry. There are various approaches to gauge port performance or efficiency. The number of containers in a TEU or tonnes of cargo is the most frequently used indicator, although there are other options as well [11]. Ports' dynamic position in global commerce has changed dramatically in the twenty-first century, owing to technological advancements, globalisation, and shifting trading patterns. However, the progress of port efficiency, productivity, and competitiveness has not been consistent across areas, notably in Africa, where ports frequently encounter infrastructural, operational, and policy issues. This research presents a unique comparative approach for evaluating the operational performance of major ports, comparing the Port of Durban, one of Africa's largest and busiest port, with prominent worldwide ports such as Singapore, Rotterdam, and Antwerp. Using analytical methods such as the Data Envelopment Analysis (DEA-BCC) and the Malmquist Productivity Index (MPI), the research intends to disclose insights into variables that influence port performance and identify practical ways to improve.

This study is unique in that it combines factual data with suggestions that are focused on policy and specific to African ports. While global ports like Singapore, Rotterdam and Antwerp have embraced digitalization, automation, and green initiatives to optimize operations, the Port of Durban offers an example of how African ports can leverage technical efficiency and resource management to remain competitive in a challenging environment. In addition to highlighting Durban's advantages, this research explores its disadvantages, offering other African ports a chance to follow in its footsteps while addressing obstacles unique to the region.

This study determines the level of operational efficiency of the seaports, measures and evaluates their productivity changes and investigates the factors influencing the productivity of the ports being studied. The traditional DEA-BCC model was applied as well as Malmquist Productivity Index. The rest of the paper includes a literature review, methodology, empirical analysis and evaluation conclusion and policy implications. The literature review covered studies highlighting their models and results. Concluding chapter is based on the results obtained from the models and policy implications is based on the overall findings.

2. Literature Review

The section will review literature on port efficiency and productivity.

Port efficiency evaluation has been the subject of several studies dating from the 1970s, employing a variety of approaches. Efficiency analysis has been routinely used by port operators to analyse their relative performance, identify possible flaws, and make recommendations for improvement [12]. As an essential component of the local economy however, a port is not just a business unit that serves many customers, such as shippers and shipping businesses, but also a driver of regional economic growth. A port that is efficient from the standpoint of the operator may not be efficient from the perspective of others. Operational efficiency according to [13] is an organization's capacity to maximize outputs whiles minimizing inputs like the utilization of time, efforts and resources. By streamlining its main operations, eliminating pointless procedures, and effectively lowering waste, a firm can reach operational efficiency. This is usually achieved by placing a strong emphasis on controlling inventory, the production process, the effective use of resources, and product distribution [14].

Previous research used a variety of approaches to evaluate and rate the efficiency of multiple ports across the world. The DEA model has been the focus of several studies for assessing port efficiency and is now the most often used to analyse port efficiency. Malmquist Productivity Index has also been adopted by recent studies alongside DEA to assess both port efficiency and productivity.

[15] employed a two-stage technique to investigate the influence of privately run terminals on the technical efficiency of Spanish ports from 2002 to 2018, a parametric (SFA) and non-parametric (DEA) technique. [16] studied the technical efficiency of 26 container terminals in India from 2015 to 2018. [17] also investigated the technical efficiency of Norwegian container ports which were evaluated relative to a frontier composed of the best performing among themselves and other comparable Nordic and UK ports. Results from the study suggested that Norwegian ports should expand their size in order to boost overall efficiency, as they are now too small for the responsibilities they undertake. Between 2002 and 2004, [18] carried out studies to examine the relative effectiveness of operations in Mercosur. The study included 15 container terminals from Brazil, 6 from Argentina, and 2 from Uruguay.

[19] used DEA to assess port efficiency of major ports in West Africa. Six ports were chosen based on their container throughput levels, and the DEA model was utilised to calculate their relative efficiencies as well as their long-term efficiencies using window analysis. The DEA model was used with a variety of port production inputs and a single output (container throughput). The Port of Tema in Ghana was found to be the most efficient West African port under evaluation. [20] assessed the efficiency of Middle Eastern container ports using the DEA-CCR

and BCC models. Their results found that 80% of the ports analysed had a positive relationship between scale and efficiency, showing increasing returns to scale. [6] investigated technical efficiency and productivity trends at Tunisia's six major commercial seaports between 2005 and 2016. The initial output-oriented DEA approach shows that the total technical efficiency at the ports is 69.4%, with a pure technical efficiency of 83.3%. Additionally, the study discovered that the average scale efficiency is roughly 82.6%, indicating that declining returns to scale are more common. [21] investigated the influence of privatisation on terminal efficiency, using the Port of Tema as a case study. This report examined the long-term efficiency patterns of the port's public and private terminals. To accomplish this goal, the DEA-CCR approach was used to compute the yearly technical efficiency trends of private and public terminals. The study's findings will help officials across the area make decisions on the efficiency and ownership structure of ports and terminals.

The operational efficiency and total factor productivity of thirty-two Chinese container terminal enterprises were evaluated in [22] between 2017-2020 using the Malmquist Productivity Index (MPI) and the highly effective Data Envelopment Analysis Slack Based Measurement (DEA-SBM) technique. [8] applied DEA analysis and the Malmquist productivity index to investigate the operational efficiency and productivity of five companies operating at the Busan New Port Container Terminal. The analysis shows an increase in average efficiency in 2018, followed by a little decrease in 2019. [23] measured the impact of port institutional improvements on efficiency gains from 2000 to 2011 using a Malmquist Index. Other research that used MPI [7] [23]-[26].

The existing literature on port efficiency and productivity has contributed significantly to understanding the operational dynamics of global ports. However, significant gaps persist, notably in terms of including African ports in globally comparative research. African ports tend to be excluded from comparative analyses with globally renowned ports, with most studies focusing primarily on the efficiency and productivity of port regions in Asia, Europe, Africa and North America, thereby ignoring African ports' representation in global port performance assessments. This article tackles this omission by including an African port, Durban, to globally renowned ports such as Singapore, Rotterdam, and Antwerp, investigating their efficiency and productivity changes simultaneously.

Furthermore, the inclusion of an African port in this study not only enriches the discourse on global port performance but also provides policy suggestions that are uniquely targeted to Africa's issues and potential. These findings can help to design more inclusive and successful ways to improve port operations across the continent. Thus, this study aims to bridge the gap in existing research by assessing the efficiency and productivity of global ports, including an African port, using a holistic measure of throughput, and producing practical suggestions for African port systems.

Lastly, while container throughput is widely used as a criterion for port efficiency in several existing research, there is less emphasis on overall port throughput, which encompasses a greater range of cargo types and represents port productivity as a whole. This study provides a more comprehensive perspective on port efficiency and productivity by taking into account overall throughput. (See **Table 1**).

Table 1. Summary of other previous studies.

Researcher	Scope	Model
[27]	Efficiency of Safaga Port (Egypt)	DEA-CCR, BCC & DEA-SBM
[28]	Efficiency of 19 sub-Saharan African Ports	DEA-MPI
[8]	Efficiency and productivity of Busan Port container terminals	DEA-MPI
[9]	Efficiency and productivity of 21 global port terminals	DEA-MPI
[29]	12 Container Terminal's Efficiency with Unexpected Output (GHG emission)	DEA-SBM
[30]	Technical efficiency and technological changes of Portuguese ports	DEA-Malmquist Tobit
[31]	Efficiency (competitiveness) of Korean and Chinese port	DEA-CCR & DEA-BCC

3. Methodology

Data Envelopment Analysis (DEA) and Malmquist Productivity Index (MPI) are covered in this section. Both DEA and MPI provide mathematical programing methods for evaluating efficiencies and productivities respectively.

3.1. Data Envelopment Analysis DEA (BCC)

The DEA model may be classified into numerous categories based on the nature of the applied problem and the specific characteristics of the data provided. Typical basic models extensively utilised for the DEA model include four; constant returns to scale (CRS) based input and output orientated CCR models, and variable return to scale (VRS) input and output orientated BCC models. DEA-CCR was first proposed by [32] and is characterized by input and output variables based on a constant return to scale. The model assumes that constant returns to scale measure the total efficiency. After that, Cooper and his colleagues continued to improve and change the model. They considered that the assumption of constant scale return had some limits, so they advocated adding variable scale return as a supplement. To evaluate technology and returns to scale, they assume that returns to scale are variable and employ the BCC model.

A few years later, [33] proposed the BCC model, with variable returns to scales (VRS). The methodology is termed input-oriented BCC model because the study used more input variables than output variables. The purpose of this model is to assess the pure technical efficiency of Decision-Making Units (DMUs) [33]. It takes into consideration inefficiencies brought on by DMU's operational size while distinguishing them from inefficiencies brought on by subpar management techniques. Mathematical formulation of BCC is as follows:

$$\begin{aligned}
&\min \theta \\
&\sum_{j=1}^{t} \lambda_j x_j \le \theta x_0 \\
&\sum_{j=1}^{t} \lambda_j y_j \ge y_0 \\
&I\lambda = 1 \\
&\lambda_j \ge 0,\ j = 1, 2, \cdots, t
\end{aligned}$$

This study used 5 input variables and 1 output variable from four major ports in the world from the year 2015 to 2023 as seen in **Table 2**.

Table 2. Input and output variables.

Variables	Input/Output
Number of berths	Input
Quay length	Input
Number of cranes	Input
Number of terminals	Input
Maximum Draught.	Input
Annual Cargo throughput (mt)	Output

3.2. Malmquist Productivity Index (MPI)

The Malmquist Productivity Index is a tool that compares the production technology of two economies and assesses efficiency changes over time by incorporating catch-up and frontier-shift terms from the Data Envelopment Analysis framework. The DEA technique is limited to determining the relative efficiency of decision units within the same time frame based solely on their magnitude. It cannot track fluctuating efficiency levels throughout periods [26]. Total Factor Productivity (TFP) measures output relative to inputs and comes from Malmquist. The Malmquist TFP index calculates the TFP change between two data points by comparing their distances to a standard technology [34]. The TFP index is applied to assess productivity change, which is divided into two components: technical efficiency changes and technological change [35].

According to the two approaches (input-oriented and output-oriented) for assessing distance functions, one can choose between an input-oriented analysis (which emphasizes efficiency improvement through reducing production inputs) or an output-oriented analysis (which emphasizes progress towards the frontier by increasing production outputs) to evaluate changes in TFP. We employ the output-oriented Malmquist productivity index model to assess port efficiency, as ports aim to maximize production by fully utilizing available inputs, assuming unchanged output and input prices.

[36] states Malmquist Productivity Index method can be represented as follows:

$$M_{oc}^{t}\left(x^{t}, y^{t}, x^{t+1}, y^{t+1}\right)=\frac{D_{oc}^{t}\left(x^{t+1}, y^{t+1}\right)}{D_{oc}^{t}\left(x^{t}, y^{t}\right)}\left[\frac{D_{oc}^{t}\left(x^{t+1}, y^{t+1}\right)}{D_{oc}^{t}\left(x^{t}, y^{t}\right)} \frac{D_{oc}^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_{oc}^{t+1}\left(x^{t}, y^{t}\right)}\right]^{\frac{1}{2}}$$

The index is calculated by multiplying two components: the efficiency changes or technical efficiency component (EFFCH), which measures the difference in relative efficiency between periods t and $t+1$, and the technology change component (TECHCH), which represents the shift in frontier technology between the two periods. **Figure 1** illustrates how technological development pushes the frontier. This converts Frontier A into Frontier B. The increase in C1 and C2 along the border is due to the phenomena known as efficiency changes, which causes the catch-up effect.

Färe *et al.* [34], categorised the catching up effect into two components: "pure" technical efficiency changes and "scale" efficiency change. That is:

$$\text{TECHNICAL EFFICIENCY} = \text{PURE TECHNICAL EFFICIENCY} * \text{SCALE EFFICIENCY}$$

$$E = PT \times S$$

If $PT > S$, the primary source of efficiency change is an increase in pure technical efficiency but if $PT < S$, the primary source of efficiency change is an improvement in scale efficiency.

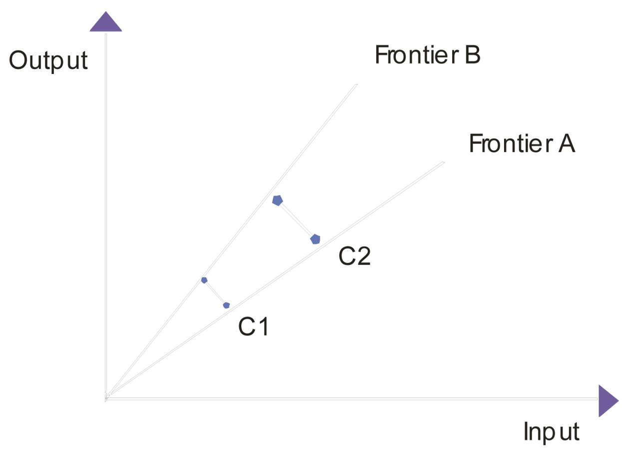

Figure 1. Malmquist productivity index decomposition.

4. Empirical Analysis and Evaluation

This section entails interpretations of the DEA and MPI models.

4.1. Operational Efficiency

The DEA approach, renowned for its remarkable efficacy, produces individual efficiency scores for each port. A score of 1 on the efficiency scale indicates that the port is operating at its optimal efficiency and successfully utilizing its resources to achieve desired outcomes. Values less than one show inefficiency, suggesting room for improving resource utilization. The data in **Table 3** demonstrates that the operational efficiency of ports in all regions had a consistent pattern of fluctuation between 2015 and 2023, with alternating periods of improved efficiency and decreasing efficiency. An alternative perspective is to view this as a recurring cycle of growth and decline.

In 2015, all four ports achieved an efficiency score of 1, indicating optimal performance and effective resource utilization. This year marked a baseline of maximum efficiency against which subsequent years could be compared. However, in 2016, a slight decline in efficiency was observed across all ports. Singapore scored 0.94523, Rotterdam 0.988878, Antwerp 0.946081, and Durban 0.938604, resulting in an average score of 0.95469825. Despite the dip, Rotterdam maintained the highest efficiency among the four, closely approaching the optimal level.

The trend continued in 2017, with Singapore and Durban returning to their optimal efficiency scores 1. In contrast, Rotterdam and Antwerp displayed minor inefficiencies, scoring 0.991098 and 0.915597, respectively. The average efficiency for this year was 0.97667375, indicating an overall improvement compared to 2016. In 2018, Singapore and Durban sustained their optimal performance. Rotterdam showed a slight improvement with a score of 0.994555, while Antwerp's efficiency increased to 0.963397. The average efficiency for this year was 0.989488, reflecting an upward trend.

Antwerp's 2019 efficiency dropped significantly to 0.84671, while Durban remained at 1. Singapore and Rotterdam scored 0.994281 and 0.981798, respectively. The overall average efficiency was 0.95569725, indicating that Antwerp needs to address specific inefficiencies. In 2020, all ports experienced declines in efficiency, with Singapore scoring 0.937489, Rotterdam 0.913586, Antwerp 0.824548, and Durban 0.973489. The average efficiency dropped to 0.912278, the lowest in the observed period, suggesting significant challenges across all ports.

The following year, 2021, continued this downward trend. Singapore's efficiency was 0.95162, Rotterdam 0.980309, Antwerp 0.804411, and Durban 0.855961. The average score of 0.89807525 underscored the widespread inefficiencies, particularly for Antwerp and Durban.

In 2022, Durban regained its optimal efficiency with a score of 1. Antwerp showed significant improvement with a score of 0.962791, while Singapore and Rotterdam scored 0.91763 and 0.977548, respectively. The average efficiency rebounded to 0.96449225.

By 2023, all ports scored below optimal efficiency. Durban led with 0.983123, followed by Singapore at 0.939014, Rotterdam at 0.917758, and Antwerp at 0.909678. The average efficiency for this year was 0.93739325, indicating persistent, albeit lesser, inefficiencies across all ports.

The analysis reveals that Durban and Rotterdam consistently performed well, with average efficiency scores close to the optimal level of 1.0, indicating moderate resource utilization and operational efficiency. Singapore also exhibited high efficiency, although minor declines in specific years brought its average to 0.965. Antwerp, however, had the lowest average efficiency score of 0.908, suggesting substantial room for improvement in resource utilization and operational practices. Furthermore, despite the fluctuating efficiency levels, the average score for the ports ranged between 0.9, which means potential resource overuse and wastage. This suggests that ports may utilize excessive resources on average to achieve desired outcomes, emphasizing the need to enhance the ratio of inputs to outputs to achieve optimal operational efficiency.

The cyclical pattern of efficiency scores highlights the dynamic nature of port operations and the potential impact of external factors on efficiency. Variability in scores across the years indicates that while some ports could return to optimal performance, others struggled with persistent inefficiencies. These could include infrastructure constraints, operational bottlenecks, or external disruptions. All ports should continuously invest in technology, process optimization, and staff training to sustain high-efficiency levels and adapt to changing operational environments.

Table 3. Results from MAXDEA software showing efficiency score.

Year	Singapore	Rotterdam	Antwerp	Durban	Average
2015	1	1	1	1	1
2016	0.94523	0.988878	0.946081	0.938604	0.95469825
2017	1	0.991098	0.915597	1	0.97667375
2018	1	0.994555	0.963397	1	0.989488
2019	0.994281	0.981798	0.84671	1	0.95569725
2020	0.937489	0.913586	0.824548	0.973489	0.912278
2021	0.95162	0.980309	0.804411	0.855961	0.89807525
2022	0.91763	0.977548	0.962791	1	0.96449225
2023	0.939014	0.917758	0.909678	0.983123	0.93739325
Average	0.96502933	0.97172556	0.90813478	0.972353	

4.2. Malmquist Productivity Index

This study delves into the productivity performance of four major ports—Singapore, Rotterdam, Antwerp, and Durban—from 2015 to 2023 (**Table 4**). The MPI is broken down into four main factors: technical efficiency (EFFCH), technology efficiency (TECHCH), pure technical efficiency (PECH), and scale efficiency (SECH). An MPI value greater than one indicates increased productivity, a value of one suggests no change and less than one signifies a decline.

In 2015/16, Durban exhibited a significant increase of 37.1% in productivity due to technical and scale efficiency improvements. Others showed a decline in productivity: Singapore had a 5.9 reduction, Rotterdam had a 2.4 decline, and

Antwerp had a 7.5 decline. Meanwhile, there was no improvement in efficiency. In 2016/17, Singapore and Durban saw productivity increases. Singapore recorded 5.8 growth because of technology improvement. Technical and scale efficiency led to 20% growth in Durban. Rotterdam and Antwerp experienced declines, with Antwerp showing some technological improvement.

Table 4. Malmquist productivity index and its determinant by ports from 2015-2023 using DEAP-xp1 program.

Port	Singapore	Rotterdam	Antwerp	Durban
factor	0	0	0	effch/sech
2015/16	0.941	0.976	0.925	1.371
factor	techch	0	techch	effch/sech
2016/17	1.058	0.937	0.949	1.2
factor	0	0	effch/sech	effch/sech
2017/18	0.883	0.986	1.052	1.037
factor	0	0	0	effch/sech
2018/19	0.958	0.919	0.853	1.233
factor	0	0	effch/sech	effch/sech
2019/20	0.903	0.878	0.974	0.962
factor	0	techch	techch	effch/sech
2020/21	0.975	1.071	0.964	1.168
factor	0	0	effch/sech	effch/sech
2021/22	0.964	0.997	1.197	1.168
factor	techch	0	techch	techch
2022/23	1.023	0.939	0.945	0.983

During 2017/18, Antwerp and Durban showed 5.2% and 3.7% productivity gains, respectively. The productivity gains in Antwerp and Durban were primarily due to technical and scale efficiency enhancements, while Singapore and Rotterdam experienced declines of 11.7% and 1.4%, respectively. For 2018/19, only Durban displayed an increase in productivity. Durban's growth was driven by improvements in technical and scale efficiency, while other ports saw declines. Singapore, Rotterdam, and Antwerp experienced 4.2%, 8.1%, and 14.7%, respectively.

All ports faced a productivity decline in 2019/20. Singapore, with a productivity decline of 9.7%, Antwerp 2.6%, and Durban 3.8%, had no significant efficiency improvements noted during this period. In 2020/21, Rotterdam and Durban improved their productivity by 7.1% and 16.8%, respectively. Rotterdam benefited from technological advancements, while Durban's improvement was due to technical and scale efficiency. Singapore and Antwerp saw declines of 2.5% and 3.6%, respectively, with Antwerp showing some improvement in technological efficiency.

In 2021/22, Antwerp and Durban continued to improve, with 19.7% and 16.8%, respectively. The improvements in Antwerp and Durban were driven by technical and scale efficiency. Singapore and Rotterdam experienced slight declines. Singapore had a 3.6% decline, and Rotterdam recorded a 0.3% productivity decline. In the final period, Singapore saw an increase in productivity of 2.3%. Singapore benefited from technological improvements, while other ports (Rotterdam 6.1%, Antwerp 5.5%, and Durban 1.7%) faced declines. Antwerp showed some technological progress, although not enough to offset the decline.

Over nine years, this comprehensive analysis of the Malmquist Productivity Index highlights varying productivity trends across the four ports. Durban consistently showed improvements driven by technical and scale efficiency, while Singapore experienced technological advancements that contributed to productivity gains in specific years. Rotterdam and Antwerp faced more fluctuating performances, with notable improvements in particular years due to technological and efficiency advancements.

The Malmquist index summary of port means, presented in Table 5, provides a comprehensive view of the average productivity performance of four major ports: Singapore, Rotterdam, Antwerp, and Durban, over a specified period.

Singapore's efficiency of 1 indicates stable technical efficiency, maintaining consistent resource utilization over time, the pure technical and scale efficiency values of 1 further support this stability in operational efficiency. However, the technology value of 3.8% suggests a slight decline in technological progress, reflected in the overall total factor productivity of 3.8%, indicating a minor reduction in total productivity. To improve, Singapore could focus on advancing its technological capabilities.

Rotterdam, like Singapore, has maintained technical efficiency at 1, along with stable pure technical and scale efficiencies. The slight decline in technology to 3.9% has led to an overall decrease in total factor productivity to 3.9%. This suggests that, like Singapore, Rotterdam's primary area for improvement lies in enhancing technological advancements to boost overall productivity.

Antwerp shows a slight improvement in technical efficiency of 1% and scale efficiency of 1%. However, its technology adoption of 3.2% indicates a minor technological decline, leading to a reduction in total factor productivity of 2.2%. Antwerp's marginal gains in technical and scale efficiencies suggest effective resource utilization and scaling, but the port could benefit from further focusing on technological improvements to enhance overall productivity.

Durban stands out with significant improvements in technical efficiency of 17.6% and scale efficiency of 17.6%, leading to an impressive total factor productivity of 13.3%. Despite a technology decline of 3.6%, similar to the other ports, Durban's overall productivity has increased due to its substantial gains in technical and scale efficiencies. This highlights Durban's effective operational strategies and resource utilization, setting a benchmark for other ports.

The Malmquist index summary underscores the importance of technological advancements and operational scalability in enhancing productivity. Ports like Durban, which have excelled in these areas, set a benchmark for others. Strategic investments in technology and optimizing scale efficiency will be crucial for ports aiming to enhance their productivity and maintain a competitive edge in the global market.

Table 5. Malmquist index summary of Port means.

Port	effch	techch	pech	sech	tfpch
Singapore	1	0.962	1	1	0.962
Rotterdam	1	0.961	1	1	0.961
Antwerp	1.01	0.968	1	1.01	0.978
Durban	1.176	0.964	1	1.176	1.133
mean	1.044	0.964	1	1.044	1.006

5. Conclusions

The examination of operational efficiency and productivity in four major worldwide container ports—Singapore, Rotterdam, Antwerp, and Durban—from 2015 to 2023 reveals a complex interaction of factors influencing their performance. Using the efficiency DEA model and the Malmquist Productivity Index (MPI), this study examined how these ports used resources, fixed inefficiencies, and reacted to changing operational circumstances.

The research of operational efficiency shows that, while all four ports experienced times of high efficiency, varying ratings over time reflect difficulty in maintaining constant performance. Durban and Rotterdam, in particular, stood out, with average efficiency scores that were near to ideal. These two ports continually maintained high levels of resource utilisation, especially during times of global economic uncertainty and external disturbances, such as the COVID-19 pandemic, which hampered operational procedures.

Singapore, despite demonstrating high efficiency in most years, had slight reductions in few years, especially 2016 and 2020. However, the port's ability to swiftly recover and achieve near-optimal ratings displays resilience and good control of operational inefficiencies. In contrast, Antwerp demonstrated more severe and persistent inefficiencies, notably beginning in 2019. Despite considerable gains in recent years, Antwerp has persistently lagged behind the other three ports, with an overall average efficiency score of 0.908.

The cyclical pattern of efficiency scores across all ports reflects the dynamic and often unpredictable nature of port operations. External influences, such as global trade fluctuations, technology developments, and regulatory changes, can have a substantial impact on a port's efficiency.

Global trade fluctuations and technological advancements have a significant impact on port efficiency and productivity. Trade volatility, caused by economic cycles, geopolitical factors, or disruptions, has an impact on cargo volumes, resulting in operational strain during trade booms and underutilisation during downturns. To remain competitive, ports must realign their strategies in response to changes in trade trends. Automation, digitalisation, and smart port technologies all contribute to increased efficiency by optimising resource allocation, reducing delays, and boosting real-time decision making. Ports such as Singapore, Rotterdam, Antwerp, and Durban demonstrate how integrating adaptive methods and cutting-edge technologies may reduce trade uncertainty while increasing efficiency, assuring competitiveness in a dynamic global trade market.

The MPI research shed light on the productivity performance of the four ports. Over a nine-year period, the MPI results showed that Durban continually achieved high levels of productivity, owing mostly to increases in technical and scale efficiency. Singapore and Rotterdam had high productivity performance, while experiencing periods of technological standstill, notably between 2015 and 2021. The fall in technological efficiency suggests that, while these ports maintained high levels of operational efficiency, they may not have completely benefited from technology developments to increase productivity.

While DEA and MPI approaches have been frequently used to assess port efficiency, many studies, like this one, rely primarily on one output variable: overall annual throughput due to data limitations. This study identifies the lack of comprehensive data on additional output variables as a key research gap, limiting the depth and accuracy of prior analyses. Future study incorporating multiple performance criteria will allow for a more rigorous assessment of port efficiency and productivity, especially for complex ports such as Singapore, Rotterdam, Antwerp, and Durban, where operational dynamics necessitate sophisticated evaluations. This broader approach might help identify operational bottlenecks and improve global port comparisons.

Policy Implications (Lessons for African Ports from the Port of Durban)

Ports play a crucial part in the growth of economy by facilitating international trade, encouraging regional integration, and assist expansion of the economy. To reach their full potential, African ports have to address inefficiencies, enhance operational performance, and follow global standards. The Port of Durban, one of Africa's largest and busiest ports, provides vital insights for other African ports seeking for modernisation, efficiency, and competitiveness. This section discusses the study's policy implications and how African ports may emulate Durban's methods.

Infrastructure Development and Modernization: The study emphasises the importance of new infrastructure in improving port efficiency and productivity. Policymakers should prioritise expenditures in port infrastructure, such as deepening berths, expanding terminals, and integrating cutting-edge cargo handling technology. Also, Public-private partnerships (PPPs) may help fund large-scale infrastructure projects, as evidenced by Durban's ability to attract private investment for infrastructure modifications.

Adoption of Technology and Digitalization: The Port of Durban's utilisation of innovative port management systems, automated cargo handling, and digital tracking technology has increased operational efficiency. African transparency and similar developments can help cut response times, promote transparency, and minimize human error. Again, Policymakers should provide regulatory frameworks that support the adoption of digital technology and offer incentives for ports to invest in automation and digital tools.

Institutional Reforms and Governance: Durban's success is due in part to effective governance and operational management. Africa's policymakers must establish autonomous port administrations with defined missions and accountability procedures to remove bureaucratic and corruption-induced inefficiencies. Decentralizing port administration and enhancing transparency in decision-making processes may provide a favourable climate for growth.

Hinterland Connectivity: The Port of Durban has robust rail and road networks that allow for smooth freight transit. African ports should work to improve multimodal transportation infrastructure, reduce bottlenecks, and promote regional integration. Additionally, policies that promote regional trade agreements and cross-border infrastructure projects can boost the economic impact of African ports on their surrounding areas.

While Durban's success in optimising operating efficiency, increasing productivity, and encouraging public-private partnerships provides essential lessons, their application to other African ports must consider the unique challenges and contexts faced by different regions.

For instance, Ports in East Africa, such as the Port of Mombasa in Kenya and the Port of Dar es Salaam in Tanzania, have grown in importance as regional trade hubs, but they face inefficiencies due to poor hinterland connection and limited integration into regional trade networks. Durban's experience in improving multimodal transportation networks and port-hinterland linkages might give useful ideas. However, these ports would have to deal with their own geographical and logistical restrictions, such as reliance on old rail connections or restricted access to finance for road network upgrades. Lessons from Durban's private-sector partnerships and investments in rail and road infrastructure could guide similar efforts, but implementation would necessitate tailored financing models, possibly incorporating regional trade agreements to improve resource sharing and economic collaboration.

In Southern and Central Africa, where ports like Walvis Bay in Namibia and Pointe-Noire in the Republic of Congo operate in less crowded trade settings, the problems are primarily focused on generating enough traffic and diversifying revenue sources. Durban's experience with competitive service pricing, improved port operations, and utilising its status as a transshipment hub provides a helpful model. However, smaller ports must tailor these techniques to their trade volumes and local economic conditions. For example, investing in scalable infrastructure and targeting port services to surrounding landlocked nations could help smaller ports replicate Durban's success on a smaller scale.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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