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EVALUATION OF TRANSSHIPMENT PRODUCTIVITY THROUGH THE IMPLEMENTATION OF THE MALMQUIST DEA METHOD. EVIDENCE FROM CIRCULAR CARGO HANDLING IN POLISH SEAPORTS

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ABSTRACT: This study evaluates the transshipment productivity of circular waste in six Polish seaports between 2013 and 2022 using the Malmquist Data Envelopment Analysis (DEA) method. The model is output-oriented and incorporates transshipped waste volumes as outputs, while inputs include quay length, maximum permissible draft, and maximum ship length. The results show that Gdynia achieved the highest productivity growth (+9.9%), followed by Darłowo (+2.8%) and Szczecin (+1%). In contrast, Świnoujście and Kołobrzeg experienced notable declines. Gdynia and Szczecin exhibited constant scale efficiency, while others suffered from scale disadvantages. Overall, total productivity increased slightly (+0.3%) over the decade, primarily due to technological change. Peaks in productivity in 2015 and 2020 correlated with significant technological improvements. These findings have practical policy implications: port authorities can benchmark their operations, identify inefficiencies, and tailor infrastructure investments to optimise the handling of circular waste. The results suggest that smaller, secondary ports – often overlooked in port research – can play a strategic role in circular supply chains if supported by proper planning and targeted modernisation. The application of Malmquist DEA in this novel cargo category and port group demonstrates the model's potential for sustainable performance evaluation in complex logistics environments.

KEYWORDS: operation, transshipment, circular economy, efficiency evaluation, Malmquist DEA Method

Abbreviations

CE –Circular Economy
 CRS – Constant Returns of Scale
 CSC – Circular Supply Chains
 IRS – Increase Returns of Scale
 TCE_EX – Exported Transshipment of Recycled Waste (CE materials)
 TCE_IM – Imported Transshipment of Recycled Waste (CE materials)
 3R – Reduce, reuse, and recycle
 LQT – Length of Quays for Transshipment
 MPD – Maximum Permissible Draft
 MLS – Maximum Length of Ships
 DEA – Data Envelopment Analysis
 SDG – Sustainable Development Goals
 EMI – Extended Malmquist Index

Introduction

In recent years, the concept of a Circular Economy (CE) has gained increasing attention in addressing the pressing environmental and sustainability challenges faced by our global community. CE is defined as an economic system that aims to eliminate waste and the continual use of resources through the reuse, sharing, repair, refurbishment, remanufacturing, and recycling of materials (Goyal et al., 2020). The shift from the traditional linear “take-make-dispose” model to a more sustainable CE form has the potential to generate significant economic, environmental, and social benefits. According to research, CE can mitigate the depletion of natural resources, reduce waste and pollution, and create both new business opportunities and employment (Medina-Mijangos et al., 2021; Geissdoerfer et al., 2018). CE is based on the principles of designing products and services to be more durable, reusable, and recyclable, thereby reducing the consumption of raw materials and the generation of waste. The concept aims to keep products, components, and materials at their highest utility and value throughout their life cycle, through strategies such as repair, reuse, remanufacturing, and recycling.

This approach not only reduces the environmental impact of production and consumption but also generates new economic opportunities, such as the development of reverse logistics systems, product-service systems, and new business models centred on circular principles. CE has emerged as a promising paradigm to address the sustainability challenges faced by modern societies (Fassio & Tecco, 2019). It focuses on minimising waste and maximising the utilisation of resources through various strategies, such as reuse, repair, and recycling (Donner et al., 2020; Urbinati et al., 2017). To assess the performance and effectiveness of CE initiatives, researchers have proposed the use of the extended Malmquist Index technique (Urbinati et al., 2020; Gupta et al., 2018). This technique is a data envelopment analysis-based approach that allows for the evaluation of productivity changes over time. It considers multiple input and output factors, such as resource consumption, waste generation, and economic performance, to provide a comprehensive assessment of the impact of CE. The application of the extended Malmquist Index technique in the context of CE has yielded valuable insights (Gupta et al., 2018; Siregar et al., 2019). Studies have found that the implementation of CE practices can lead to improvements in productivity, resource efficiency, and environmental performance. For example, one study analysing the circular business models of European manufacturing companies showed that the adoption of CE principles resulted in a reduction of waste and more efficient use of resources. Another study highlighted the potential for big data analytics to support the implementation of CE strategies, emphasising the importance of stakeholder collaboration and a holistic, systems-level approach (Gupta et al., 2018). The extended Malmquist Index technique has proven to be a valuable tool in evaluating the performance of CE initiatives. By considering multiple input and output factors, this approach provides a comprehensive assessment of CE’s impact, enabling policymakers and practitioners to make informed decisions and drive sustainable development.

The study aims to assess changes in the productivity of the transshipment of circulating waste in seaports and to identify related technological changes and economies of scale. The study selected Polish ports as the target sample due to their suitability for analyses related to the circular economy. Despite their limited capacity for handling large vessels owing to insufficient technical infrastructure, these secondary ports possess ample potential to expand activities such as transshipment, storage, industrial operations, distribution, and logistics. This capacity can position them as key contributors to circular supply chains. Furthermore, the crucial role of stevedores is instrumental in fostering this development. These workers, who are adept at adapting to shifting market trends, proactively seek out new cargo types to replace those no longer available and adjust their services accordingly, driving the advancement of circular supply chain operations at these secondary ports. Consequently, the studied ports play a vital role as active participants in the land transport networks of circular supply chain cargo (Czermański et al., 2024).

An overview of the literature

In the context of seaport operations, productivity refers to the efficient utilisation of resources, including labour, equipment, and infrastructure, to maximise the throughput of cargo and vessels. Productivity in seaports is a critical measure of performance, as it directly impacts the cost-effectiveness and competitiveness of a port (Singh et al., 2022).

Seaport productivity can be measured in various ways, such as the number of containers or cargo units handled per hour, the turnaround time of vessels, or the utilisation of equipment and labour. Measuring productivity helps port authorities and operators identify areas for improvement and benchmark their performance against industry standards. However, measuring productivity in seaports can be challenging due to the complexity of the operations and the multitude of factors that can influence it. For example, factors such as weather conditions, cargo mix, and the efficiency of hinterland connections can all impact the overall productivity of a seaport. Seaport productivity can be measured in various ways, such as the number of containers handled per hour, the turnaround time of vessels, or the utilisation of crane and yard capacity. Improving productivity is essential for seaports to remain competitive, as it allows them to handle more cargo with the same resources, reduce congestion, and provide faster service to customers (Berhe et al., 2015). Productivity can be influenced by a range of factors, including the availability and condition of equipment, the skills and training of workers, the efficiency of operational processes, and the use of technology and automation (Singh et al., 2022; Berhe et al., 2015; Wacker et al., 2006). Investing in new equipment, implementing process improvements, and adopting digital technologies can all contribute to enhancing seaport productivity (Wacker et al., 2006; Sharma, 2014).

Efficiency in seaport operations refers to the optimal utilisation of resources to achieve the desired outcomes. Efficiency is closely related to productivity, but it focuses more on the process of converting inputs into outputs, rather than just the overall throughput. In the context of seaports, efficiency can be measured in terms of the ratio of actual output to the maximum potential output, given the available resources. Efficient seaport operations involve minimising waste, reducing downtime, and optimising the use of labour, equipment, and infrastructure (Teng, 2014).

Achieving efficiency in seaport operations requires a holistic approach that considers various aspects, such as workforce management, equipment maintenance, process optimisation, and the adoption of technology (Berhe et al., 2015). Efficient seaport operations can lead to cost savings, improved customer satisfaction, and a more sustainable business model.

The notion of CE has garnered significant attention as a revolutionary strategy for accomplishing the Sustainable Development Goals (SDGs). It highlights the necessity for a comprehensive change in patterns of consumption and production to guarantee the sustainability of the environment and promote social equity. Based on the literature review, several important premises can be drawn supporting the need to implement the concept of CE:

- a) CE is acknowledged as a potential driver for socioeconomic and environmental advantages, with challenges covering technological, organisational, financial, institutional, and social elements (Pla-Julián & Guevara, 2019).
- b) Empirical studies indicate a statistically significant association between CE activities and the achievement of SDGs, notably in the European Union (Rodríguez-Anton et al., 2019).

- c) Achieving the SDGs' goals for cheap, clean energy, living on land, decent employment and economic growth, clean water and sanitation, and responsible consumption and production are all directly impacted by CE practices (Valverde and Avilés-Palacios, 2021; Schroeder et al., 2019).
- d) Reaching the SDGs depends on the convergence of Industry 4.0 and CE, which offers creative approaches to sustainable business models and the production process (Dantas, 2021).
- e) Although CE places a lot of emphasis on process redesign and material recycling, it is criticised for not having a significant social component, which is crucial for a comprehensive approach to sustainable development (Murray et al., 2015).
- f) Reduce, reuse, and recycle (3R) business models are driving businesses in emerging economies toward sustainable practices that mitigate resource shortages and environmental concerns (Goyal et al., 2018).
- g) By reducing waste via reuse and recycling, CE is suggested as a self-sufficient economic model that may improve sustainability and productivity (Mehta, 2023).
- h) Industrial symbiosis and regional collaboration are emphasised as successful CE business models that may greatly increase resource efficiency and aid in the accomplishment of the SDGs (Cudečka-Puriņa et al., 2022).

As a transformational force for attaining the SDGs, CE is becoming increasingly acknowledged. It provides an approach for reconsidering economic actions in a way that encourages resource efficiency, social justice, and environmental preservation. To effectively solve global sustainability concerns, it is critical to integrate CE principles into technical innovation and regional collaboration, as shown by the study synthesis. Seaports participate in the implementation of the assumptions of the CE concept as a link in reverse logistics (Mańkowska et al., 2020).

The importance of seaports as key hubs in the shift to CE – one that prioritises sustainability and resource efficiency – is becoming more widely acknowledged. The way ports do business has changed because of this transformation, with greater emphasis on social and environmental issues, along with waste reduction and increased local economic advantages. Dutch ports are used as case studies to highlight the importance of ports for the CE initiatives. This is especially true in urban regions where there is a high concentration of end-of-life items, which presents ports with both possibilities and challenges (de Langen & Sornn-Friese, 2019). Adopting CE can help ports reduce the detrimental effects of their activities on the communities around them and bring additional advantages to the local economy (Roberts, 2021). What is more, and worth emphasising, is that it is important to note that secondary ports could play a major role in Circular Supply Chains by expanding their transshipment, warehousing, industrial, distribution, and logistical operations, even despite their constraints in processing large ships. However, secondary ports face several obstacles when implementing CE practices, such as managing return-flow uncertainty, transportation and infrastructure problems, identifying appropriate supply chain partners, coordinating and exchanging information, product traceability, cultural concerns, and internal resistance to change (Mańkowska et al., 2020).

The effectiveness and productivity evaluations are critical for seaports to increase competitiveness and adapt to the changing needs of global economic activities (Mańkowska et al., 2020; Mańkowska et al., 2021). The effectiveness and productivity of seaports, which are vital hubs in international trade and supply networks, are assessed using the non-parametric Malmquist DEA technique (Wang et al., 2022; Huang, 2022; Osundiran & Okonta, 2018). The Extended Malmquist Index (EMI) technique is a widely recognised and extensively employed method in the field of productivity and efficiency analysis, offering a robust framework for evaluating the performance of various entities, such as companies, industries, or even countries. This technique provides a comprehensive understanding of the factors influencing productive and financial performance, enabling researchers and practitioners to uncover the intricate relationships between technological, market, and other significant variables. The EMI technique builds upon the traditional Malmquist Index, which was initially developed by Caves, Christensen, and Diewert in the 1980s (Rabat et al., 2017). The EMI, as the name suggests, incorporates additional factors beyond the traditional inputs and outputs, allowing for a more nuanced and insightful analysis. Recent studies have demonstrated the versatility and applicability of the EMI technique across diverse domains. In the context of the Moroccan public hospital network, the technique revealed a decline in productivity gain from 2017/2018, followed by an improvement in 2018/2019. This information can be valuable for hospital administrators and policymakers in identifying areas for improvement and implementing targeted strategies to enhance

the efficient utilisation of resources. Furthermore, the EMI technique has been employed to examine the relationships between productivity, efficiency, utilisation, and quality in various industries, including healthcare. The technique provides a framework for understanding the complex interplay between these factors, enabling organisations to optimise their operations and deliver superior outcomes.

Research methods

The Malmquist DEA technique, which is frequently supplemented by other models such as the EBM (Wang et al., 2021; Nguyen et al., 2022) or alternative DEA techniques (Pannala et al., 2023; Seth & Feng, 2020), is an effective tool for evaluating the efficiency and productivity of port transshipment processes. This approach is used in many studies that concentrate on various seaports throughout the world, including those in Korea (Pham & Kim, 2022), Tunisia (Ben Mabrouk et al., 2022), Europe (Nguyen et al., 2022), Vietnam (Nguyen et al., 2019), and Norway (Odeck & Schøyen, 2020). These studies examine efficiency and productivity patterns, outlining areas for improvement and discovering best-performing seaports by merging the Malmquist DEA results. A thorough evaluation of seaport operations is made possible by the Malmquist DEA technique, which also provides insights into changes in productivity, efficiency, and competitiveness in the marine sector. The technique not only assesses present performance but also offers information on productivity growth, technological advancements, and technical efficiency (Nadarajan et al., 2023; Barros et al., 2018).

The EMI technique is a powerful tool for analysing productivity changes in complex systems, such as seaports, where multiple inputs and outputs are involved. This approach can be particularly useful in evaluating the impact of technological advancements, changes in trade patterns, and the implementation of sustainable practices on the overall performance and efficiency of seaport operations. One key aspect of the EMI technique is its ability to decompose productivity changes into different components, such as technological change, technical efficiency change, and scale efficiency change (Charnes et al., 1978). This allows researchers and policymakers to identify the specific drivers of productivity growth or decline and tailor their strategies accordingly. For example, a recent study using the EMI technique found that the inefficiency observed in container ports was primarily due to scale, rather than technical inefficiency (Charnes et al., 1978). This suggests that port authorities should focus on optimising the operational scale of their facilities, rather than simply investing in more inputs, to improve overall efficiency.

Evaluating the productivity and performance of entities, such as nations or regions, in a variety of areas, including waste management, is another of use for the Malmquist model in DEA. Because it measures changes in productivity and efficiency over time, this approach can be very helpful in evaluating the CE elements of waste management. Examining variations in solid waste management performance over time while taking economic and environmental aspects into account is possible using the Malmquist Total Factor Productivity Index. In one research project, two models were developed: one centred on economic performance, utilising public sector investment and expenditures to optimise recycling and recovery ratios, and the other on environmental performance using waste management factors (Tüzüner & Alp, 2018). An EMI technique, which integrates a cooperative game network DEA, may assess the overall, subsystem, and factor efficiency of industrial CE systems. With the use of this technique, the EMI may be thoroughly broken down into dynamic indicators of efficiency change and technical advancement, exposing differences in efficiency across different cities and industrial CE subsystems (Ding et al., 2020). The Malmquist model and its variants are useful tools for assessing the efficacy of waste management systems in CE. To properly comprehend the effectiveness and productivity of waste management services, it is crucial to take environmental indicators into account. They make this possible by allowing the examination of both economic and environmental factors. By tracking the advancement of waste management methods toward sustainability goals, these tools can assist managers and policymakers in identifying areas for improvement.

The Malmquist DEA model is a widely used approach for measuring productivity changes over time, and the EMI is a variation of this model that provides additional insights (Guajardo, 2015). The EMI technique allows for the evaluation of production efficiency while considering the presence of ratio inputs and outputs, which is a common occurrence in many real-world applications. This approach is particularly useful in situations where the production function is unknown or difficult to

specify, as it does not require the assumption of a specific functional form (Guajardo, 2015; Francis & Visser, 2020). The use of the EMI has been demonstrated in various fields, such as assessing organisational efficiency and workforce diversity (Guajardo, 2015), ranking decision-making units using Pythagorean fuzzy DEA models (Saini et al., 2020), and estimating the influence of extraction method and processing location on forest harvesting efficiency. These studies have shown that the extended Malmquist Index can provide valuable insights into the scale characteristics of the production technology, including the identification of the most productive scale size and the measurement of scale and overall efficiency (Guajardo, 2015; Francis and Visser, 2020; Saini et al., 2020; Olesen et al., 2022). The ability to incorporate ratio inputs and outputs is a key advantage of this approach, as it allows for a more accurate representation of the underlying production processes.

The study aims to assess changes in the productivity of the transshipment of circular waste in seaports and to identify technological changes and their economies of scale. Malmquist Data Envelopment Analysis was used as the tool in the research procedure:

$$m_o(y_{t+1}, x_{t+1}, y_t, x_t) = \left[\frac{d_o^t(x_{t+1}, y_{t+1})}{d_o^t(x_t, y_t)} \times \frac{d_o^{t+1}(x_{t+1}, y_{t+1})}{d_o^{t+1}(x_t, y_t)} \right]^{\frac{1}{2}} \quad (1)$$

where:

m = Malmquist Index,

o = output-oriented,

d = distance matrix,

x = inputs matrix,

y = outputs matrix,

t = base period,

t+1 = next period after the base period.

It should be added that productive port efficiency is expressed in three ways (Merk and Dang, 2012):

- an efficient production frontier that maximises port output for varying input levels,
- an efficient production frontier-based benchmark of best practices,
- observable gaps between what ports produce at present and what they would optimally produce if they were operating efficiently.

By measuring current inefficiencies against the most efficient ports and taking into account relative differences in production volumes, input utilizations, and approved technologies, the efficiency indicator is able to measure the inefficiencies (Merk & Dang, 2012).

The Malmquist DEA model is output-oriented, with numerous inputs and multiple effects built into its design. The data envelopment analysis technique is a non-parametric approach to effectiveness analysis and assessment. Unlike traditional and advanced econometric approaches, this methodology does not need to determine the functional form (specifying, estimating, and verifying). The number of variables and their associations do not need to be reduced, unlike in econometric models. The Malmquist DEA model assumes:

- outputs: volume of exported waste as transshipment in seaports (for each seaport and each sector), the volume of imported waste as transshipment in seaports (for each seaport and each sector),
- inputs: lengths of quays for transshipment, maximum permissible drafts of ships, and the maximum lengths of the ships.

The data used in this study were collected in close cooperation with port authorities and port-operating companies. Given the decentralised nature of data sources, one of the key challenges involves the need to standardise heterogeneous data inputs and to classify diverse types of cargo into appropriate waste categories and further into circular waste groups, aligned with relevant classification systems. Undertook a meticulous data harmonisation process to ensure consistency and comparability across ports and years. Another limitation stemmed from the inherent complexity of the dataset, which included a wide variety of circular waste types (e.g., ash, glass cullet, biomass, scrap, etc.) reused in several sectors (e.g., construction, steel, energy). This required breaking down aggregated figures into analytically meaningful components. Despite potential inconsistencies or missing values, particularly in earlier years or at smaller ports, efforts were made to validate and cross-check data

with internal reports. That prioritised the objectivity, consistency, and quality of the dataset, employing triangulation of sources where possible. As a result, the final dataset provides a robust basis for comparative analysis, albeit with the acknowledgement that classification ambiguities could influence port-level outcomes. The reliance on this data also limited the inclusion of qualitative factors (e.g., operational disruptions, port policies) that may have influenced efficiency. Another important limitation concerns the selection of input and output variables used in the Malmquist DEA model. While quay length, maximum permissible draft, and maximum vessel length were appropriate infrastructural proxies, they do not fully capture the operational complexity and performance dynamics of waste transshipment processes. Key efficiency determinants, such as cargo dwell time, the availability and capacity of handling equipment, workforce size, frequency of vessel calls, hinterland connectivity, and the degree of digitalisation or automation, were not included due to data limitations. Additionally, the study does not control for external variables that could significantly affect transshipment productivity over time. These include changes in environmental regulations, shifts in waste classification standards, economic disruptions (e.g., the COVID-19 pandemic), fluctuations in commodity prices, and policy-driven incentives for circular economy practices. The exclusion of such exogenous factors limits the interpretability of year-to-year changes in productivity, as some variations may be driven by external influences rather than internal efficiency or technological progress. Future research should consider integrating such variables or adopting hybrid models to better isolate endogenous efficiency effects.

Results of the research

The analysis used secondary data for 6 seaports in Poland in 2013-2022: Darłowo, Gdańsk, Gdynia, Kołobrzeg, Szczecin, and Świnoujście. They are all located in the Baltic Sea basin. The ports in Gdańsk, Gdynia, Szczecin, and Świnoujście are strategic destinations, while the ports in Darłowo and Kołobrzeg are regional. The analysis included data such as the transshipment of recycled waste in the export relation (TCE_EX; in thousand tonnes), the transshipment of recycled waste in the import relation (TCE_IM; in thousand tonnes), the length of the quays (LQT; in meters), maximum permissible draft (MPD; in meters) and the maximum length of the ships (MLS; in meters). Transshipment of circular waste concerned the following types of waste: expellers, pulp, meal, oilcake, wheat bran, gypsum, ash, coal tar, glass cullet, scrap, slag, biomass, biomass pellets, tires, sulfuric acid, and post-sulfite lye. They are reused in the construction and chemical, energy, steel, and food sectors. Table 1 presents the main characteristics of the analysed ports.

Table 1. Description of selected navigation and infrastructure conditions of the examined ports (in 2013-2022)

Variables	TCE_EX	TCE_IM	LQT	MPD	MLS
	thousand tonnes		meters		
Ports	output 1	output 2	input 1	input 2	input 3
Darłowo	9.8	5.2	350.9	4.0	75.0
Gdańsk	105.7	84.5	10053.0	15.0	300.0
Gdynia	59.4	556.1	10726.7	13.5	340.0
Kołobrzeg	15.4	0.0	726.2	5.5	100.0
Szczecin	124.0	102.1	11041.8	9.2	215.0
Świnoujście	50.5	70.2	6534.6	13.5	270.0

Source: authors' work based on (Statistics Poland 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022) and internal data from seaports.

Table 1 indicates that the longest quay for transshipment (average value from 2013-2022 – values have varied) was at the seaport in Szczecin (approx. 11 km), Gdynia (approx. 10.7 km), and Gdańsk (approx. 10 km). The ports with the highest maximum allowable ship draft were Gdańsk (15

m), Gdynia (13.5 m), and Świnoujście (13.5 m). The Gdynia and Gdańsk seaports allowed ships of up to 340 m and 300 m in length throughout the research period. In analysing exported circular waste for the years 2013-2022, the largest average volume was recorded in Szczecin (124 thousand tonnes) and Gdańsk (105.7 thousand tonnes), while the smallest occurred in Darłowo (9.8 thousand tonnes) and Kołobrzeg (15.4 thousand tonnes). However, it was the seaport in Gdynia that imported most of this waste – the average volume in the analysed research period was 556.1 thousand tonnes. A high value was also recorded for Szczecin (102.1 tonnes). The lowest value of the average volume of imports of circular waste in the examined period was recorded in Darłowo (5.2 thousand tonnes). The seaport in Kołobrzeg was the only one that did not import this type of cargo in 2013-2022.

Table 2 shows the Malmquist productivity index (total factor productivity change – TFPch) of circular waste transshipment in the 2013-2022 analysed period. The results show changes to the previous year, and the geometric mean covers the entire research period. The table also includes changes in pure efficiency, scale efficiency, the catching-up effect, and technology.

Table 2. Malmquist productivity index of circular waste transshipment by years

Year	Pure efficiency change	Scale efficiency change	Efficiency change (catch-up effect)	Technological change	Total factor productivity change
2014	0.917	1.007	0.924	1.222	1.129
2015	0.924	0.992	0.917	1.277	1.171
2016	0.870	0.998	0.869	0.805	0.700
2017	1.049	0.991	1.040	1.008	1.048
2018	0.956	0.998	0.954	1.060	1.012
2019	1.046	1.019	1.065	1.053	1.122
2020	0.977	0.994	0.971	1.253	1.217
2021	0.999	1.015	1.014	1.023	1.038
2022	1.152	0.898	1.035	0.714	0.739
Geometric mean	0.985	0.99	0.975	1.029	1.003

Source: authors' work based on (Statistics Poland 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022) and internal data from seaports.

As can be seen from Table 2, the levelized productivity factor for the last 9 years for all the analysed Polish ports experienced a slight improvement in productivity (by about 0.3%), although there were years where productivity relative to the previous year was high. The highest increase in seaport productivity was recorded in 2020 by about 21.7% compared to 2019, which was mainly due to a significant increase in technological progress (by about 25.3%). The highest technological progress was recorded in 2015 relative to 2014, followed by 2020 relative to 2019 and 2014 relative to 2013 (by about 22.2%). In 2015 and 2022, there was a regression in the total productivity of circular waste handling at all ports in general. These results are a product of changes in the pure efficiency of the ports' circular waste handling and economies of scale, which affected the change in efficiency (catch-up effect). The rates of change in pure efficiency suggest that the studied ports were efficient only in 2017, 2019, and 2022, compared to each previous year, the other years being characterised by inefficiency. However, in 2014, 2019, and 2021, there was a change in the economies of scale (an increase), while in the others, unfortunately, there were disadvantages of scale or a decrease in the economies of scale. The result of these two quantities is important in assessing the catch-up effect. The highest catch-up (or even overtaking) effect was recorded in 2019, thanks to economies of scale, and in 2017 and 2022, thanks to pure efficiency. A small overtaking effect was also recorded in 2022 due to an increase in economies of scale. However, from the averaged values, over the entire period under study, the ports were inefficient (pure efficiency) and experienced mainly lagging effects (lack of sufficiently rapid responses to market changes) while technological progress was made. Against this background, it is worthwhile to present the situation of individual ports over the entire period

under study (Table 3), with detailed results for the ports in individual years being included in the supplementary material – see Appendix 2 (the distance analysis is included in the supplementary material – see Appendix 1).

Table 3. Malmquist productivity index of circular waste transshipment by ports

Port	Pure efficiency change	Scale efficiency change	Efficiency change (catch-up effect)	Technological change	Total factor productivity change
Darłowo	1	0.972	0.972	1.058	1.028
Gdańsk	0.998	0.985	0.983	1.011	0.994
Gdynia	1	1	1	1.099	1.099
Kołobrzeg	1	0.983	0.983	0.982	0.966
Szczecin	1	1	1	1.010	1.010
Świnoujście	0.914	0.999	0.913	1.018	0.930
Geometric mean	0.985	0.99	0.975	1.029	1.003

Source: authors' work based on (Statistics Poland 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022) and internal data from seaports.

Based on Table 3, the ports of Darłowo, Gdynia, Kołobrzeg, and Szczecin were efficient in terms of pure efficiency related to total circular waste handling over the entire study period. The seaports of Gdańsk and Świnoujście, on the other hand, were inefficient throughout the period under study. Some diseconomies of scale were experienced throughout the 2013–2022 – time horizon by the ports of Darłowo, Gdańsk, Kołobrzeg, and Świnoujście, while the ports of Gdynia and Szczecin had constant scale effects. Therefore, a catch-up effect was recorded at Darłowo, Gdańsk, Kołobrzeg, and Świnoujście, due to being too slow to respond to the market. The diseconomies of scale in those seaports may result from:

- the limitation of reloading equipment (including those with a longer range), which are also used to service larger ships,
- barriers related to the coordination of transshipment (including waste) at the port hinterland, lack of an effective possibility of coordinating supply chains due to the lower frequency of port calls, and the need to maintain larger stocks in warehouses,
- increase in port congestion in the sea-land chain (congestion),
- availability of cargo storage space (including waste) – impossibility of future market expansion,
- limited space and inability to quickly respond to changes,
- displacement of waste by higher value cargo (container before bulk cargo, and others),
- the need to achieve similar ship traffic due to the lack of capital-intensive infrastructure investments (related to obtaining greater drafts),
- limited number of ports that can accommodate larger ships requiring larger drafts (port of call problem),
- dispersed import or export demand, smaller volumes of waste transported on one vessel,
- insufficient proximity of suppliers or recipients of waste – external diseconomies of scale.

Moreover, the five ports surveyed (except Kołobrzeg) experienced technological progress, with the highest technological progress¹ being recorded in the seaports of Gdynia and Darłowo. In summary, increases in the productivity of circular waste handling were recorded in the seaports of Gdynia (by about 9.9%), Darłowo (by about 2.8%), and Szczecin (by about 1%). The seaports of Gdańsk saw a slight regression in this indicator by about 0.6%, Kołobrzeg (by about 3.4%), and the seaport of Świnoujście (by about 7%).

1 In terms of the change in technological efficiency over time.

Discussion

This study presents novel insights into the transshipment productivity of circular economy (CE) waste in Polish seaports using the Malmquist DEA methodology. The results show that although some ports achieved productivity gains, others exhibited declining or stagnant performance, largely due to inefficiencies or technological stagnation. These findings align with prior research indicating that performance differentials across ports can stem from discrepancies in infrastructure, investment capabilities, and the institutional support for CE practices (Roberts et al., 2021; Pannala et al., 2023; Mańkowska et al., 2020; Guldmann & Huulgaard, 2023). The observed technological progress in ports like Gdynia and Darłowo suggests a growing adoption of CE-friendly practices, potentially supported by investments in equipment modernisation or digital infrastructure. This supports the argument by Roberts et al. (2021) that technological and organisational innovation is essential for ports seeking to align with CE principles. However, the relatively flat or negative productivity trends in other ports point to barriers such as inefficient resource allocation or lack of integration with industrial symbiosis networks (Tovar & Wall, 2022; Cudečka-Puriņa et al., 2022).

Notably, ports such as Gdańsk and Świnoujście, despite their strategic positions, underperformed in terms of pure efficiency and economies of scale. This outcome reinforces the idea that physical capacity alone does not guarantee productivity improvements unless accompanied by systemic optimisation and policy support (Notteboom et al., 2022; Castellano et al., 2020). Moreover, the results confirm that performance improvements in ports are more likely when operational strategies are aligned with long-term sustainability frameworks (González-Cancelas et al., 2025; Molavi et al., 2019).

One critical limitation of this study lies in the DEA model's inability to account for external shocks or qualitative contextual factors. For example, fluctuations in transshipment productivity during 2020–2022 may have been influenced by the COVID-19 pandemic, shifts in EU waste regulation, or disruptions in regional logistics flows. That is why there is a need for hybrid models that integrate external variables to better capture dynamic system changes (Kunambi & Zheng, 2024).

This research reinforces the strategic potential of secondary ports within CE logistics chains. Ports like Kołobrzeg or Darłowo, though limited in scale, may serve niche functions in circular supply chains (Mańkowska et al., 2020). However, tapping this potential requires overcoming structural constraints, such as inconsistent cargo flows, limited economies of scale, and underdeveloped CE ecosystems. This study confirms also the relevance of the Malmquist DEA method in capturing the productivity dynamics of circular waste transshipment. The method's ability to decompose efficiency from technological change offers a valuable analytical lens. However, future research should aim to integrate environmental and social indicators into port productivity models, in line with the broader goals of sustainable development.

The results of this study provide actionable insights for port authorities, particularly in the context of planning and managing transshipment operations of circular economy (CE) waste. By identifying specific inefficiencies, such as scale disadvantages, limited technical efficiency, or insufficient technological progress, port authorities can benchmark their performance against best-performing facilities like Gdynia or Szczecin. These findings may support more informed decisions on investments in digital infrastructure, coordination with hinterland logistics, and service models adapted to the characteristics of CE cargoes.

From a policy and regulatory standpoint, the results emphasise the need for tailored reforms that reflect the logistical and material complexity of CE cargo. Current waste legislation at both national and EU levels often fails to account for the characteristics of secondary ports or the specificity of CE flows. Adjustments could include improved classification schemes for recyclables, simplified permitting procedures for intermodal CE shipments, and stronger incentives for infrastructure projects enhancing regional waste valorisation capacity. These frameworks should also recognise that certain circular cargoes, such as biomass, combustion by-products, or scrap, require differentiated treatment, given their strategic role in energy and industrial transitions.

Moreover, a shift in perception is needed among port authorities regarding CE cargo. Instead of viewing such flows merely as waste, residues, or low-value products, ports should position CE cargo handling as part of the broader green port transition. Biomass, for example, represents a viable short-term alternative to coal in thermal power generation, while steel manufacturers are increasingly sub-

stituting iron ore with scrap metal. Port service models must adapt to support these macroeconomic trends. Beyond upgrading existing handling capabilities, port estates should accommodate distribution terminals and even production facilities dedicated to CE-based processes. This includes creating operational space for manufacturers seeking to transform circular inputs into final products directly in port-adjacent zones. Regulatory updates are also critical. In Poland, existing provisions discriminate against imported biomass relative to domestic sources, limiting market flexibility. Further, stable support mechanisms are needed for low-value CE cargoes – such as coal combustion by-products – which often remain stockpiled due to a lack of end-market coordination. Market instruments are also necessary to mitigate extreme price volatility, especially in sectors like ferrous scrap. Lastly, long-term legal uncertainty surrounding a potential ban on GMO soybean meal imports continues to undermine investment planning in port agroterminals.

Looking ahead, future research should move beyond the traditional focus on how ports enable circular flows and instead examine how CE dynamics influence port development. Relevant avenues include identifying the factors that determine why specific ports are integrated into CE logistics chains, strategies for stabilising circular cargo flows to enable long-term planning, and the role of CE cargo in transforming port throughput structures, especially as traditional bulk segments like coal or iron ore decline. The use of real-time operational data in DEA models could improve responsiveness to changing logistics conditions. Moreover, extending the analysis to other European ports would facilitate cross-country comparisons and support the construction of CE-oriented performance typologies. Finally, integrating environmental and social dimensions into Malmquist DEA frameworks, such as emissions reduction or green job creation, would enhance the capacity of such models to assess CE performance in ports holistically.

Conclusions

This study, using Malmquist Data Envelopment Analysis, provides valuable insights into the transshipment productivity of circular waste in six Polish seaports between 2013 and 2022. By employing an output-oriented model and considering factors like quay length, maximum permissible draft, and ship length as inputs, the research quantifies the efficiency of waste transshipment operations. The findings reveal variations in productivity levels across the analysed seaports, highlighting areas for potential improvement. The application of the Malmquist Index allows for the decomposition of productivity change into efficiency change and technological change, offering a nuanced understanding of the factors driving performance differences. This analysis contributes to the broader discussion on sustainable port management and the role of CE principles in the maritime sector.

However, the study acknowledges certain limitations. The reliance on secondary data may introduce potential biases or inaccuracies. Additionally, the chosen input and output variables, while relevant, may not capture the full complexity of waste transshipment operations. Furthermore, the study focuses solely on Polish seaports, limiting the generalizability of the findings to other geographical contexts.

The observed variations in transshipment productivity across the six Polish seaports raise important questions about the factors influencing performance. Differences in infrastructure, management practices, and local regulations could contribute to the observed disparities. The study's findings underscore the need for port authorities to adopt a data-driven approach to optimise waste transshipment operations. By identifying best practices and implementing targeted improvements, ports can enhance their efficiency and contribute to a more sustainable maritime industry. The study also highlights the potential of DEA as a valuable tool for benchmarking and performance evaluation in the context of circular waste management.

Several challenges emerged during the research process. Data collection proved to be a significant hurdle, particularly in accessing reliable and consistent data across all six seaports. The complexity of the Malmquist DEA model also posed a challenge, requiring careful consideration of input and output variable selection and interpretation of the results. Furthermore, the dynamic nature of the maritime industry and the evolving landscape of circular economy practices necessitate ongoing monitoring and evaluation of transshipment productivity.

This study represents a significant methodological and thematic innovation in the field of port performance analysis. For the first time in the academic literature, the productivity of circular waste transshipment operations has been evaluated using the Malmquist Data Envelopment Analysis (DEA) method. While previous studies have predominantly focused on major ports and conventional cargo types such as containers or bulk goods, this research shifts the attention to an underexplored cargo category – circular waste – and to secondary ports, which are often overlooked despite their growing importance in regional logistics and circular economy frameworks. The application of the Malmquist DEA approach in this specific context not only fills a critical gap in existing research but also establishes a new analytical foundation for assessing environmental and operational performance at the micro-regional level. The findings of this study have important implications for future research and policy development, offering a data-driven basis for enhancing sustainability and efficiency in maritime waste management practices.

This study identifies several gaps in existing research that warrant further investigation. Limited research exists on the specific application of Malmquist DEA to circular waste transshipment in seaports. Future studies could explore the impact of different policy interventions, technological innovations, and stakeholder collaborations on transshipment productivity. Additionally, comparative analyses across different countries or regions could provide valuable insights into best practices and inform policy development. Further research is also needed to explore the social and environmental dimensions of circular waste transshipment, considering factors such as job creation, community impacts, and greenhouse gas emissions.

Based on the findings and limitations of this study, the following recommendations are proposed for future research:

Expand the scope of analysis: Future studies should consider a wider range of seaports, both domestically and internationally, to enhance the generalizability of the findings.

Incorporate additional variables: Explore the inclusion of other relevant input and output variables, such as energy consumption, waste composition, and treatment methods, to provide a more comprehensive assessment of transshipment productivity.

Employ qualitative research methods: Complement quantitative analysis with qualitative data collection, such as interviews and case studies, to gain a deeper understanding of the contextual factors influencing productivity.

Investigate the impact of policy and technology: Analyse the effects of different policy instruments and technological innovations on waste transshipment efficiency and sustainability.

Develop a framework for best practices: Based on comparative analyses and best practice identification, develop a framework for optimising circular waste transshipment operations in seaports.

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The contribution of the authors

Conceptualisation, M.P. and E.S.; literature review, A.O.-J. and E.S.; methodology, E.S. and M.P.; formal analysis, I.K. and A.O.-J.; writing, E.C., I.K., A.O.-J., M.P. and E.S.; conclusions and discussion, E.C. and A.O.-J.

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References

- Barros, C., Chen, Z., Antunes, J. J. M., & Wanke, P. (2018). Malmquist productivity indexes in Chinese ports: A fuzzy GMSS DEA approach. *International Journal of Shipping and Transport Logistics*, 10(2), 202–226. <https://doi.org/10.1504/IJSTL.2018.10010282>
- Ben Mabrouk, M., Elmsalmi, M., Aljuaid, A. M., Hachicha, W., & Hammami, S. (2022). Joined efficiency and productivity evaluation of Tunisian commercial seaports using DEA-based approaches. *Journal of Marine Science and Engineering*, 10(5), 626. <https://doi.org/10.3390/jmse10050626>
- Berhe, E., Abebe, B. G., & Azene, D. K. (2015). A new perspective on productivity measurement. *Total Quality Management & Business Excellence*, 28(1-2), 205–217. <https://doi.org/10.1080/14783363.2015.1053804>
- Castellano, R., Ferretti, M., Musella, G., & Risitano, M. (2020). Evaluating the economic and environmental efficiency of ports: Evidence from Italy. *Journal of Cleaner Production*, 271, 122560. <https://doi.org/10.1016/j.jclepro.2020.122560>
- Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research*, 2(6), 429–444. [https://doi.org/10.1016/0377-2217\(78\)90138-8](https://doi.org/10.1016/0377-2217(78)90138-8)
- Cudečka-Puriña, N., Atstāja, D., Koval, V., Purviņš, M., Nesenenko, P., & Tkach, O. (2022). Achievement of sustainable development goals through the implementation of the circular economy and developing regional cooperation. *Energies*, 15(11), 4072. <https://doi.org/10.3390/en15114072>
- Czermański, E., Kotowska, I., Oniszczyk-Jastrzębek, A., Pluciński, M., & Szaruga, E. (2024). Factors influencing the adoption of circular economy practices in Polish seaports: An analysis of determinants and challenges. *Frontiers in Marine Science*, 11, 1465204. <https://doi.org/10.3389/fmars.2024.1465204>
- Dantas, T. E. T., de-Souza, E. D., Destro, I. R., Hammes, G., Rodriguez, C. M. T., & Soares, S. R. (2021). How the combination of circular economy and Industry 4.0 can contribute towards achieving the Sustainable Development Goals. *Sustainable Production and Consumption*, 26, 213–227. <https://doi.org/10.1016/j.spc.2020.10.005>
- de Langen, P., & Sornn-Friese, H. (2019). Ports and the circular economy. In R. Bergqvist & J. Monios (Eds.), *Green ports: Inland and seaside sustainable transportation strategies* (pp. 85–108). Elsevier. <https://doi.org/10.1016/B978-0-12-814054-3.00005-0>
- Ding, L., Lei, L., Wang, L., & Zhang, L. (2020). Assessing industrial circular economy performance and its dynamic evolution: An extended Malmquist index based on cooperative game network DEA. *Science of the Total Environment*, 731, 139001. <https://doi.org/10.1016/j.scitotenv.2020.139001>
- Donner, M., Gohier, R., & de Vries, H. (2020). A new circular business model typology for creating value from agro-waste. *Science of the Total Environment*, 716, 137065. <https://doi.org/10.1016/j.scitotenv.2020.137065>
- Nguyen, D., Gyei-Kark, P., & Choi, P.-H. (2019). The performance analysis of container terminals in Vietnam using DEA-Malmquist. *Journal of Navigation and Port Research*, 43(2), 101–109. <https://doi.org/10.5394/KINPR.2019.43.2.101>
- Fassio, F., & Tecco, N. (2019). Circular economy for food: A systemic interpretation of 40 case histories in the food system in their relationships with SDGs. *Systems*, 7(3), 43. <https://doi.org/10.3390/systems7030043>
- Francis, O., & Visser, R. (2020). Estimating the influence of extraction method and processing location on forest harvesting efficiency – A categorical DEA approach. *European Journal of Forest Engineering*, 6(2), 60–67. <https://doi.org/10.33904/ejfe.722822>
- Geissdoerfer, M., Morioka, S. N., Carvalho, M. M. D., & Evans, S. (2018). Business models and supply chains for the circular economy. *Journal of Cleaner Production*, 190, 712–721. <https://doi.org/10.1016/j.jclepro.2018.04.159>
- González-Cancelas, N., Guil López, J. J., Vaca-Cabrero, J., & Camarero-Orive, A. (2025). Toward smart and sustainable port operations: A blue ocean strategy approach for the Spanish port system. *Journal of Marine Science and Engineering*, 13(5), 872. <https://doi.org/10.3390/jmse13050872>
- Goyal, S., Chauhan, S., & Mishra, P. (2020). Circular economy research: A bibliometric analysis (2000–2019) and future research insights. *Journal of Cleaner Production*, 287, 125011. <https://doi.org/10.1016/j.jclepro.2020.125011>
- Goyal, S., Esposito, M., & Kapoor, A. (2018). Circular economy business models in developing economies: Lessons from India on reduce, recycle, and reuse paradigms. *Thunderbird International Business Review*, 60(5), 729–740. <https://doi.org/10.1002/tie.21883>
- Guajardo, S. A. (2015). Assessing organizational efficiency and workforce diversity. *Public Personnel Management*, 44(2), 239–265. <https://doi.org/10.1177/0091026015575179>
- Gupta, S., Chen, H., Hazen, B. T., Kaur, S., & González, E. D. S. (2018). Circular economy and big data analytics: A stakeholder perspective. *Technological Forecasting and Social Change*, 144, 466–474. <https://doi.org/10.1016/j.techfore.2018.06.030>
- Huang, L. (2022). Research on logistics efficiency of Chinese ports above designated size based on DEA-Malmquist index. In *Proceedings of the 2nd International Conference on Enterprise Management and Economic Development* (pp. 113–118). Atlantis Press. <https://doi.org/10.2991/aebmr.k.220603.020>

- Kunambi, M. M., & Zheng, H. (2024). Contextual comparative analysis of Dar es Salaam and Mombasa port performance by using a hybrid DEA(CVA) model. *Logistics*, 8(1), 2. <https://doi.org/10.3390/logistics8010002>
- Mańkowska, M., Kotowska, I., & Pluciński, M. (2020). Seaports as nodal points of circular supply chains: Opportunities and challenges for secondary ports. *Sustainability*, 12(9), 3926. <https://doi.org/10.3390/su12093926>
- Mańkowska, M., Pluciński, M., & Kotowska, I. (2021). Biomass sea-based supply chains and the secondary ports in the era of decarbonization. *Energies*, 14(7), 1796. <https://doi.org/10.3390/en14071796>
- Medina-Mijangos, R., Zein, S., Rojas, H. R. G. G., & Seguí, L. (2021). The economic assessment of the environmental and social impacts generated by a light packaging and bulky waste sorting and treatment facility in Spain: A circular economy example. *Environmental Sciences Europe*, 33(1), 78. <https://doi.org/10.1186/s12302-021-00519-6>
- Mehta, S. (2023). Circular economy and sustainable development goals. *MET Management Review*, 10, 24–29. <https://doi.org/10.34047/mmr.2020.10103>
- Merk, O. M., & Dang, T.-T. (2012). Efficiency of world ports in container and bulk cargo (oil, coal, ores and grain). *OECD Regional Development Working Papers*, 9. <https://doi.org/10.1787/5k92vgw39zs2-en>
- Molavi, A., Lim, G. J., & Race, B. (2019). A framework for building a smart port and smart port index. *International Journal of Sustainable Transportation*, 14(9), 686–700. <https://doi.org/10.1080/15568318.2019.1610919>
- Murray, A., Skene, K., & Haynes, K. (2015). The circular economy: An interdisciplinary exploration of the concept and application in a global context. *Journal of Business Ethics*, 140(3), 369–380. <https://doi.org/10.1007/s10551-015-2693-2>
- Nadarajan, D., Ahmed, S. A. M., & Noor, N. F. M. (2023). Seaport network efficiency measurement using triangular and trapezoidal fuzzy data envelopment analyses with liner shipping connectivity index output. *Mathematics*, 11(6), 1454. <https://doi.org/10.3390/math11061454>
- Nguyen, P. H., Nguyen, T. L., Nguyen, T. G., Nguyen, D. T., Tran, T. H., Le, H. C., & Phung, H. T. (2022). A cross-country European efficiency measurement of maritime transport: A data envelopment analysis approach. *Axioms*, 11(5), 206. <https://doi.org/10.3390/axioms11050206>
- Notteboom, T., Pallis, A., & Rodrigue, J.-P. (2022). *Port economics, management and policy (1st ed.)*. London: Routledge. <https://doi.org/10.4324/9780429318184>
- Odeck, J., & Schøyen, H. (2020). Productivity and convergence in Norwegian container seaports: An SFA-based Malmquist productivity index approach. *Transportation Research Part A: Policy and Practice*, 137, 222–239. <https://doi.org/10.1016/j.tra.2020.05.001>
- Olesen, O. B., Petersen, N. C., & Podinovski, V. V. (2022). Scale characteristics of variable returns-to-scale production technologies with ratio inputs and outputs. *Annals of Operations Research*, 318, 383–423. <https://doi.org/10.1007/s10479-022-04862-6>
- Osundiran, A. O., & Okonta, F. (2018). Malmquist data envelopment analysis as a tool to evaluate the productivity levels of container ports in developing countries located in East and Southern Africa. *Central European Review of Economics & Management*, 2(2), 81–99. <https://doi.org/10.29015/CEREM.573>
- Pannala, R. K. P. K., Bhanu Prakash, N., & Mogha, S. K. (2023). Efficiency measurement at major ports of India during the years 2013–14 to 2018–19: A comparison of results obtained from DEA model and DEA with Shannon entropy technique. In M. Thakur, S. Agnihotri, B.S. Rajpurohit, M. Pant, K. Deep & A.K. Nagar (Eds.) *Lecture Notes in Networks and Systems* (547, pp. 603–614). Springer. https://doi.org/10.1007/978-981-19-6525-8_46
- Pla-Julián, I., & Guevara, S. (2019). Is circular economy the key to transitioning towards sustainable development? Challenges from the perspective of care ethics. *Futures*, 105, 67–77. <https://doi.org/10.1016/j.futures.2018.09.001>
- Pham, T. Q. M., & Kim, H. (2022). Analysis of efficiency and productivity for major Korean seaports using PCA-DEA model. *Journal of Korea Port Economic Association*, 38(2), 123–138. <https://doi.org/10.38121/KPEA.2022.38.2.123>
- Rabat, A., Bonnet, P., Drissi, K. E. K., & Girard, S. (2017). Analytical models for electromagnetic coupling of an open metallic shield containing a loaded wire. *IEEE Transactions on Electromagnetic Compatibility*, 59(5), 1634–1637. <https://doi.org/10.1109/TEM.2017.2661579>
- Roberts, T., Williams, I., Preston, J., Clarke, N., Odum, M., & O’Gorman, S. (2021). A virtuous circle? Increasing local benefits from ports by adopting circular economy principles. *Sustainability*, 13(13), 7079. <https://doi.org/10.3390/su13137079>
- Rodriguez-Anton, J. M., Rubio-Andrada, L., Celemin-Pedroche, M. S., & Alonso-Almeida, M. D. M. (2019). Analysis of the relations between circular economy and Sustainable Development Goals. *International Journal of Sustainable Development & World Ecology*, 26(8), 708–720. <https://doi.org/10.1080/13504509.2019.1666754>
- Saini, N., Gandotra, N., Bajaj, R. K., & Dwivedi, R. P. (2020). Ranking of decision-making units in Pythagorean fuzzy CCR model using data envelopment analysis. *Materials Today: Proceedings*, 33(7), 3884–3888. <https://doi.org/10.1016/j.matpr.2020.06.243>

- Schroeder, P., Anggraeni, K., & Weber, U. (2019). The relevance of circular economy practices to the Sustainable Development Goals. *Journal of Industrial Ecology*, 23(1), 77–95. <https://doi.org/10.1111/jiec.12732>
- Seth, S., & Feng, Q. (2020). Assessment of port efficiency using stepwise selection and window analysis in data envelopment analysis. *Maritime Economics & Logistics*, 22, 536–561. <https://doi.org/10.1057/s41278-020-00155-6>
- Singh, S., Solkhe, A., & Gautam, P. (2022). What do we know about employee productivity? Insights from bibliometric analysis. *Journal of Scientometric Research*, 11(2), 183–198. <https://doi.org/10.5530/jscires.11.2.20>
- Siregar, D. I., Hinggo, T. H., & Zaki, H. (2019). Circular economy framework in recycling company: Exploratory study. In *Proceedings of the 1st International Conference on Contemporary Islamic Studies (ICCEIST 2019)* (pp. 75–78). Atlantis Press. <https://doi.org/10.2991/iccelst-ss-19.2019.16>
- Sharma, S. (2014). Productivity or production: Appraising growth solution for Indian SMEs. *International Journal of Economics & Management Sciences*, 3(3), 1000185. <https://doi.org/10.4172/2162-6359.1000185>
- Statistics Poland. (2024a, January 8). *Transport – Activity results in 2022*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2022,6,18.html>
- Statistics Poland. (2024b, January 8). *Transport – Activity results in 2021*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2021,6,17.html>
- Statistics Poland. (2024c, January 8). *Transport – Activity results in 2020*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2020,6,16.html>
- Statistics Poland. (2024d, January 8). *Transport – Activity results in 2019*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2019,6,15.html>
- Statistics Poland. (2024e, January 8). *Transport – Activity results in 2018*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2018,6,14.html>
- Statistics Poland. (2024f, January 8). *Transport – Activity results in 2017*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2017,6,13.html>
- Statistics Poland. (2024g, January 8). *Transport – Activity results in 2016*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2016,6,12.html>
- Statistics Poland. (2024h, January 8). *Transport – Activity results in 2015*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2015,6,11.html>
- Statistics Poland. (2024i, January 8). *Transport – Activity results in 2014*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2014,6,10.html>
- Statistics Poland. (2024j, January 8). *Transport – Activity results in 2013*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2013,6,9>
- Statistics Poland. (2024k, January 8). *Transport – Activity results in 2012*. <https://stat.gov.pl/en/topics/transport-and-communications/transport/transport-activity-results-in-2012,6,8.html>
- Teng, H. S. S. (2014). Qualitative productivity analysis: Does a non-financial measurement model exist? *International Journal of Productivity and Performance Management*, 63(2), 250–256. <https://doi.org/10.1108/IJPPM-03-2013-0034>
- Tovar, B., & Wall, A. (2022). The relationship between port-level maritime connectivity and efficiency. *Journal of Transport Geography*, 98, 103213. <https://doi.org/10.1016/j.jtrangeo.2021.103213>
- Tüzüner, Z., & Alp, İ. (2018). Comparison of solid waste management performances of Turkey and EU countries associated with Malmquist index. *Politeknik Dergisi*, 21(1), 75–81. <https://doi.org/10.2339/politeknik.386857>
- Urbanati, A., Chiaroni, D., & Chiesa, V. (2017). Towards a new taxonomy of circular economy business models. *Journal of Cleaner Production*, 168, 487–498. <https://doi.org/10.1016/j.jclepro.2017.09.047>
- Urbanati, A., Rosa, P., Sassanelli, C., Chiaroni, D., & Terzi, S. (2020). Circular business models in the European manufacturing industry: A multiple case study analysis. *Journal of Cleaner Production*, 274, 122964. <https://doi.org/10.1016/j.jclepro.2020.122964>
- Valverde, J.M., & Avilés-Palacios, C. (2021). Circular Economy as a Catalyst for Progress towards the Sustainable Development Goals: A Positive Relationship between Two Self-Sufficient Variables. *Sustainability*, 13. <https://doi.org/10.3390/SU132212652>
- Wacker, J. G., Yang, C., & Sheu, C. (2006). Productivity of production labor, non-production labor, and capital: An international study. *International Journal of Production Economics*, 103(2), 863–872. <https://doi.org/10.1016/j.ijpe.2005.12.012>
- Wang, C. N., Nguyen, P. H., Nguyen, T. L., Nguyen, T. G., Nguyen, D. T., Tran, T. H., Le, H. C., & Phung, H. T. (2022). A two-stage DEA approach to measure operational efficiency in Vietnam's port industry. *Mathematics*, 10(9), 1385. <https://doi.org/10.3390/math10091385>
- Wang, C. N., Nguyen, N. A. T., Fu, H. P., Hsu, H. P., & Dang, T. T. (2021). Efficiency assessment of seaport terminal operators using DEA Malmquist and epsilon-based measure models. *Axioms*, 10(2), 48. <https://doi.org/10.3390/axioms10020048>

Supplementary materials

Supplementary material 1. Distances for Malmquist DEA for seaports in 2013-2022

YEAR	Port	crs te rel to tech in yr			VRS
		t-1	t	t+1	TE
2013	Darłowo	0	0.888	0.48	1
	Gdańsk	0	1	1.027	1
	Gdynia	0	1	1.028	1
	Kołobrzeg	0	1	0.804	1
	Szczecin	0	1	1.002	1
	Świnoujście	0	0.898	0.774	0.9
2014	Darłowo	2.234	1	0.558	1
	Gdańsk	1.13	1	1.037	1
	Gdynia	0.998	1	0.85	1
	Kołobrzeg	0.899	0.723	0.52	0.76
	Szczecin	1.21	1	0.905	1
	Świnoujście	0.798	0.687	0.569	0.706
2015	Darłowo	1.791	1	2.837	1
	Gdańsk	0.764	0.77	0.751	0.775
	Gdynia	1.348	1	0.78	1
	Kołobrzeg	0.796	0.573	0.847	0.623
	Szczecin	1.346	1	1.33	1
	Świnoujście	0.747	0.671	0.776	0.693
2016	Darłowo	0.653	1	1.092	1
	Gdańsk	0.361	0.431	0.437	0.44
	Gdynia	1.439	1	0.963	1
	Kołobrzeg	0.416	0.617	0.61	0.67
	Szczecin	0.81	1	1.132	1
	Świnoujście	0.407	0.477	0.473	0.492
2017	Darłowo	1.113	1	0.937	1
	Gdańsk	0.658	0.659	0.624	0.692
	Gdynia	1.143	1	0.986	1
	Kołobrzeg	0.634	0.627	0.57	0.686
	Szczecin	0.997	1	0.954	1
	Świnoujście	0.393	0.389	0.37	0.408
2018	Darłowo	1.107	1	0.891	1
	Gdańsk	0.826	0.783	0.622	0.822
	Gdynia	1.035	1	1.07	1
	Kołobrzeg	0.465	0.423	0.37	0.467
	Szczecin	1.048	1	1.342	1
	Świnoujście	0.384	0.366	0.339	0.385

YEAR	Port	crs te rel to tech in yr			VRS
		t-1	t	t+1	TE
2019	Darłowo	1.141	1	0.759	1
	Gdańsk	1.293	1	0.858	1
	Gdynia	0.996	1	0.912	1
	Kołobrzeg	0.398	0.348	0.268	0.371
	Szczecin	0.844	1	0.859	1
	Świnoujście	0.55	0.51	0.413	0.522
2020	Darłowo	1.391	1	1.231	1
	Gdańsk	1.283	1	0.843	1
	Gdynia	1.306	1	1.133	1
	Kołobrzeg	0.456	0.351	0.393	0.381
	Szczecin	1.299	1	0.921	1
	Świnoujście	0.513	0.424	0.375	0.443
2021	Darłowo	0.968	1	2.062	1
	Gdańsk	1.312	1	2.022	1
	Gdynia	1.067	1	0.923	1
	Kołobrzeg	0.443	0.497	1.004	0.506
	Szczecin	1.09	1	1.006	1
	Świnoujście	0.352	0.326	0.48	0.331
2022	Darłowo	0.579	0.686	0	1
	Gdańsk	0.561	0.856	0	0.983
	Gdynia	1.137	1	0	1
	Kołobrzeg	0.425	0.86	0	1
	Szczecin	1.011	1	0	1
	Świnoujście	0.255	0.395	0	0.399

Source: authors' work based on (Statistics Poland 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022) and internal data from seaports.

Supplementary material 2. Detailed Malmquist Index for seaports in 2013-2022

Year	Port	Pure efficiency change	Scale efficiency change	Efficiency change (catch-up effect)	Technological change	Total factor productivity change
2014	Darłowo	1	1.126	1.126	2.032	2.289
	Gdańsk	1	1	1	1.049	1.049
	Gdynia	1	1	1	0.985	0.985
	Kołobrzeg	0.76	0.952	0.723	1.243	0.899
	Szczecin	1	1	1	1.099	1.099
	Świnoujście	0.784	0.975	0.765	1.161	0.888

Year	Port	Pure efficiency change	Scale efficiency change	Efficiency change (catch-up effect)	Technological change	Total factor productivity change
2015	Darłowo	1	1	1	1.791	1.791
	Gdańsk	0.775	0.993	0.77	0.979	0.753
	Gdynia	1	1	1	1.259	1.259
	Kołobrzeg	0.819	0.967	0.792	1.39	1.101
	Szczecin	1	1	1	1.22	1.22
	Świnoujście	0.982	0.994	0.977	1.159	1.132
2016	Darłowo	1	1	1	0.48	0.48
	Gdańsk	0.567	0.988	0.56	0.926	0.519
	Gdynia	1	1	1	1.358	1.358
	Kołobrzeg	1.077	1	1.077	0.675	0.727
	Szczecin	1	1	1	0.781	0.781
	Świnoujście	0.71	1.002	0.712	0.858	0.611
2017	Darłowo	1	1	1	1.01	1.01
	Gdańsk	1.574	0.97	1.527	0.993	1.516
	Gdynia	1	1	1	1.089	1.089
	Kołobrzeg	1.023	0.993	1.016	1.012	1.028
	Szczecin	1	1	1	0.938	0.938
	Świnoujście	0.829	0.982	0.814	1.01	0.823
2018	Darłowo	1	1	1	1.087	1.087
	Gdańsk	1.188	1.001	1.189	1.055	1.255
	Gdynia	1	1	1	1.024	1.024
	Kołobrzeg	0.681	0.992	0.675	1.1	0.742
	Szczecin	1	1	1	1.048	1.048
	Świnoujście	0.944	0.997	0.941	1.05	0.988
2019	Darłowo	1	1	1	1.131	1.131
	Gdańsk	1.217	1.049	1.277	1.276	1.629
	Gdynia	1	1	1	0.965	0.965
	Kołobrzeg	0.794	1.036	0.822	1.144	0.941
	Szczecin	1	1	1	0.793	0.793
	Świnoujście	1.355	1.029	1.394	1.079	1.504
2020	Darłowo	1	1	1	1.354	1.354
	Gdańsk	1	1	1	1.223	1.223
	Gdynia	1	1	1	1.197	1.197
	Kołobrzeg	1.027	0.982	1.009	1.299	1.311
	Szczecin	1	1	1	1.23	1.23
	Świnoujście	0.848	0.982	0.832	1.221	1.017

Year	Port	Pure efficiency change	Scale efficiency change	Efficiency change (catch-up effect)	Technological change	Total factor productivity change
2021	Darłowo	1	1	1	0.887	0.887
	Gdańsk	1	1	1	1.248	1.248
	Gdynia	1	1	1	0.97	0.97
	Kołobrzeg	1.33	1.064	1.416	0.892	1.263
	Szczecin	1	1	1	1.088	1.088
	Świnoujście	0.748	1.029	0.769	1.104	0.849
2022	Darłowo	1	0.686	0.686	0.64	0.439
	Gdańsk	0.983	0.87	0.856	0.57	0.487
	Gdynia	1	1	1	1.11	1.11
	Kołobrzeg	1.974	0.877	1.731	0.495	0.856
	Szczecin	1	1	1	1.002	1.002
	Świnoujście	1.205	1.005	1.211	0.662	0.802

Source: authors' work based on (Statistics Poland 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022) and internal data from seaports.

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OCENA WYDAJNOŚCI PRZEŁADUNKOWEJ POPRZECZ WDROŻENIE METODY MALMQUIST DEA. DOŚWIADCZENIA Z OBSŁUGI ŁADUNKÓW GOSPODARKI OBIEGU ZAMKNIĘTEGO W POLSKICH PORTACH MORSKICH

STRESZCZENIE: W artykule oceniono produktywność przeładunków odpadów cyrkularnych w sześciu polskich portach morskich w latach 2013–2022 przy użyciu analizy obwiedni danych Malmquista (Malmquist DEA). W badaniu zastosowano model DEA zorientowany na wyniki, biorąc pod uwagę ilość eksportowanych i importowanych odpadów jako wyniki, z długością nabrzeża, maksymalnym dopuszczalnym zanurzeniem i maksymalną długością statku jako danymi wejściowymi. Wyniki pokazują, że największy wzrost produktywności osiągnął port w Gdyni (+9.9%), następnie w Darłowie (+2.8%) i Szczecinie (+1%). Natomiast w Świnoujściu i Kołobrzegu odnotowano wyraźne spadki. Gdynia i Szczecin wykazywały stałą efektywność skali, podczas gdy pozostałe porty cierpiały z powodu niekorzystnych efektów skali. Ogólnie dla wszystkich portów, całkowita produktywność wzrosła nieznacznie (+0,3%) w ciągu dekady, głównie dzięki zmianom technologicznym. Szczyty produktywności w latach 2015 i 2020 korelowały ze znaczącymi postępami technologicznymi. Wyniki te mają praktyczne znaczenie dla polityki portowej: władze portowe mogą porównywać swoją działalność, identyfikować nieefektywności i dostosowywać inwestycje infrastrukturalne w celu optymalizacji obsługi odpadów cyrkularnych. Badanie sugeruje, że mniejsze, drugorzędne porty – choć często pomijane w badaniach portowych – mogą odgrywać strategiczną rolę w cyrkularnych łańcuchach dostaw, jeśli zostaną odpowiednio zaplanowane i zmodernizowane. Zastosowanie metody Malmquista DEA do tej nowej kategorii ładunków i grupy portów pokazuje potencjał tego modelu w ocenie zrównoważonej wydajności w złożonych środowiskach logistycznych.

SŁOWA KLUCZOWE: operacje portowe, przeładunek, gospodarka obiegu zamkniętego, ocena wydajności, metoda Malmquist DEA