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Factors influencing the adoption of circular economy practices in polish seaports: an analysis of determinants and challenges

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The purpose of the article is to fill the research gap in identifying and prioritizing the factors that determine the choice of a port for handling circular supply chains (CSC). To this end, Polish seaports handling CSC cargo with an average turnover of at least 100,000 tons in the last 10 years were analyzed. The authors analyzed CSC cargo occurring in seaports, in two stages, both in terms of quantity and quality. The first stage involved an analysis of the literature and the European Commission's programs on the development of the Circular Economy (CE), followed by an analysis of the relationship between the size of the port, measured by the average volume of cargo handled at the studied port, and the average share of CSC cargo in total cargo handling. On the other hand, in the second stage, based on face-to-face interviews, the factors that determine the choice of a particular port for handling CSC cargo were extracted. The study revealed a significant relationship between port size and the share of CSC cargo in total cargo handling. Furthermore, the research identified and prioritized key factors influencing the choice of ports for CSC, providing valuable insights for port authorities and policymakers. These findings can serve as a foundation for further academic research aimed at optimizing port operations within circular supply chains and advancing the theoretical framework of circular economy logistics. Port authorities and businesses can leverage these insights to enhance strategic decision-making, improve operational efficiency, and strengthen their competitive advantage in the circular economy landscape.

KEYWORDS
circular economy, port selection, sustainable logistics, Polish seaports, cargo handling factors

1 Introduction

In the context of the global shift towards a more sustainable and environmentally conscious economic model, the role of ports has become increasingly crucial in the implementation and advancement of circular economy principles. Ports, as hubs of trade and transportation, possess significant potential to contribute to the transition towards a circular economy by adopting innovative practices and fostering collaboration among various stakeholders. Ports around the world are recognizing the benefits and opportunities presented by the circular economy, with a recent study indicating a 60% increase in future interest in adopting circular economy principles among port authorities (Alamoush et al., 2021).

A circular economy is defined as an alternative model that minimizes resource depletion, waste, and emissions (Geissdoerfer et al., 2020). A circular economy integrates reduction, reuse, and recycling operations for sustainable development in an effort to break the link between economic growth and development and the use of limited resources (Padilla-Rivera et al., 2020). The circular economy raises living standards while promoting waste reduction, resource conservation, and environmental preservation (Popović and Radivojevic, 2022). Through the “inclusion” of resources, circular economy activities seek to sever the connection between unsustainable patterns of production and consumption (Bjørnbet et al., 2021). Circular economy practices entail changing how goods and services are produced, consumed, and disposed of, with recycling being the most common strategy for reintroducing materials into the system (Mhatre et al., 2021). Circular economy practices include raising customer knowledge, enacting legislation and policies, cultivating a circular economy culture, raising awareness among supply chain partners, and creating goods with a circular economy mindset (Khan and Haleem, 2021).

One of the key aspects of ports’ involvement in the circular economy is their ability to collaborate with the wider supply chain and their local communities. Maritime transport is a nexus of the global supply chains, and ports have a crucial role to play in green supply and global value chains (Fredouet, 2023). Furthermore, ports’ deep integration within their local hinterlands means they can significantly impact the economic activity and sustainability of their surrounding areas (Roberts et al., 2021).

However, ports also face various challenges in their pursuit of circular economy practices. The adaptation to the redesign of supply and distribution networks, as well as the limited physical space for redevelopment, can hinder ports’ ability to fully embrace circular economy principles (Roberts et al., 2021). Despite these challenges, the potential and willingness of ports to be at the forefront of the transition to a circular economy have been identified (Alamoush et al., 2021). By adopting a collaborative and integrated approach, involving key stakeholders such as logistics providers, local governments, and supply chain partners, ports can unlock the benefits of the circular economy and contribute to a more sustainable and resilient economic system.

The purpose of this article is to fill the research gap in identifying and prioritizing the factors that determine the choice of a port for handling reverse supply chains. To achieve the above goal, specific questions were formulated:

1. what cargo occurring in seaports can be classified as CSC cargo?
2. for which ports can CSC cargo be an important area of port activity?
3. what factors determine the choice of a particular port for handling CSC cargo?

In order to answer the above research questions, the article:

- identified and classified the main CSC cargo occurring in seaports,
- determined the relationship between the size of the port (port cargo handling) and the share of CSC cargo handling in total cargo handling, identified and prioritized the factors that determined the choice of a particular port for handling CSC cargo.

Polish ports were selected as the target sample of the study due to. They are secondary ports and are predisposed to analyses related to the circular economy. The secondary ports, though limited in their ability to handle large vessels due to insufficient technical infrastructure, have ample room to expand activities such as transshipment, storage, industrial operations, distribution, and logistics. This potential can position them as key contributors to circular supply chains. Additionally, the role of stevedores is crucial in fostering this development. These workers, who are quick to adapt to shifting market trends, are proactive in finding new types of cargo to replace those that are no longer available, and adjust their services accordingly, driving the advancement of circular supply chain operations at these secondary ports (Mańkowska et al., 2020). Therefore, the studied ports play an important role as active participants in the land transport chains of CSC cargo.

2 Literature review

Seaports are quickly becoming crucial hubs for circular operations that integrate logistics, sustainability, and production. They adapt to the concepts of the circular economy through the implementation of cooperative waste management, and the creation of circular activities (Kovačič Lukman et al., 2022). Seaports concentrate on industrial growth, waterfront projects, and maritime clusters to mitigate negative effects and benefit the local community (Ferreira et al., 2022). To encourage industrial growth, waterfront economies, and circular manufacturing activities, ports must modify their business models (de Langen et al., 2020; de Martino, 2022). Cutting-edge models that highlight sustainability and waste management in port operations, such as waste-to-clean energy systems at ports, show the viability and additional value of circular approaches (Karimpour et al., 2019). Seaports that embrace circularity concepts can improve waste management procedures, develop new energy sources, and streamline overall port operations (Ferreira et al., 2022). Evaluating seaports' circular operations using established indicators and the 9 R-strategy transitions can reveal information about their sustainability and circularity value (Kovačič Lukman et al., 2022).

Seaports successfully conduct recycling programs using a variety of ways. One method involves the use of Green Port concepts based on circular economy principles, as seen in Bali, Indonesia, where waste from various port activities is recycled to generate new energy and improve sustainability (Ferreira et al., 2022). Furthermore, the green port concept stresses environmental quality, energy and resource utilization, waste management, and habitat quality, all of which are critical for achieving green port hub status and increasing port competitiveness, as proven in the case study of Port Klang in Malaysia (Jeevan et al., 2023).

In Poland, the idea of "green ports," which integrate economic, social, and environmental elements, is still in its infancy and is intended to promote sustainable growth (Oniszczuk-Jastrząbek et al., 2018). The importance of Polish seaports to the country's economy has led to an increase in interest in corporate social responsibility (CSR) in these ports (Michalska-Szajer et al., 2021). Ports in Poland must implement sustainable development plans and operations to solve social and environmental challenges (Dziennik Ustaw, 2023) while retaining public approval to satisfy the needs of growing global trade (Adamowicz and Puszkarski, 2018). Because of the Baltic Sea's vulnerability, the environmental performance of Polish ports is crucial, highlighting the necessity of environmental management systems and adherence to regulatory standards (McCallum, 2022). In general, there is an effort to guarantee the long-term viability of Polish ports by striking a balance between economic expansion and social and environmental concerns. Seaports in Poland are gradually implementing sustainable principles through bottom-up efforts by port authorities, supported by local and regional authorities, to adapt to sustainable economy principles (Bocheński et al., 2021). Seaports in Poland, like Szczecin, adapt to circular economy principles by utilizing secondary ports for sustainable supply chains, facing challenges like infrastructure, coordination, and cultural issues (Mańkowska et al., 2020). By adopting circularity, seaports enable a more economically and environmentally sustainable port ecosystem by fostering creative business models, enhancing sustainability, and producing new energy sources from waste. In general, the circular economy encourages ports to innovate, work with stakeholders, and find new ways to prosper in a more sustainable and circular future. Through circular activities, ports are acknowledged as vital centers that may improve economic competitiveness, job prospects, and investments while reducing adverse effects (Sacco and Cerreta, 2022; Roberts et al., 2021). With a suggested framework to improve cooperation and the adoption of circular practices for mutual advantages, seaports have a clear chance to lead the worldwide shift to a circular economy (Kovačič Lukman et al., 2022).

Table 1 presents some seaports that have introduced a circular economy. Based on a literature review, they were assigned types of recovered/recycled waste.

An extension of the concept of the circular economy along with its practical impact on the functioning of selected seaports is presented in Table 2. Research to date has mainly focused on the role of seaports in the development of CE through their impact on waste treatment, the development of reverse supply chains, and the creation of a waste treatment port industry. Few studies show how CSC cargo can influence port development. However, there are no studies showing the relationship between port size and the importance of CSC cargo on port operations or development opportunities. Nor does the research to date show the factors that determine the choice of a port as a link in reverse supply chains, or which cargo occurring in seaports can be classified as CSC cargo.

The concept of a circular economy has gained considerable attention in recent years as a way of addressing complex and pressing sustainability challenges. One area that has received particular attention in this regard is the role of seaports, which play a key role in the movement of goods and materials in an urban context. Seaports are often located in historic city centres and are well placed to act as hubs for circular economy initiatives, such as the reuse and repurposing of buildings and land. However, implementing circular economy strategies in seaports can be challenging and there is a need for a more systematic approach to assessing and monitoring progress. To address this need, research is underway to develop criteria and indicators to assess the performance of the circular economy in seaports. Research on circular economy indicators for ports is still in an exploratory phase, characterised by a lack of in-depth studies on the development of port-related circular economy indicators. Faut et al. extracted a set of relevant and feasible CE indicators to support port authorities as well as port stakeholders in monitoring the ongoing CE transformation. Through a multi-method qualitative study, a feasible list of 12 CE indicators for ports was developed. Seven of these are highly feasible and five have medium feasibility in terms of relevance to stakeholders and ease of implementation (Faut et al., 2023). In contrast, Courtens et al. analysed the process of transitioning to a circular economy, which included six steps in the identification or discovery phase for each project: (1) identification of supply-side boundary conditions for deliberate discovery of a circular economy initiative; (2) identification of demand-side boundary conditions for deliberate discovery of a circular economy initiative using reference projects in other ports; (3) matching the dual boundary conditions (see 1 and 2) with available locations in the port area under consideration; (4) assessing the economic promise of circular economy initiative prospects that may include port users; (5) identifying a 'coalition of the willing' around promising circular economy initiative prospects; (6) matching available locations (see 3) with the most promising circular economy initiative prospects (see 4 and 5) in the port (Courtens et al., 2023). Based on a semi-systematic analysis of the literature review and a SWOT analysis, Barona et al. examined CE practices in seaports and the potential of adopting closed-loop business models to create value for port stakeholders and contribute to the United Nations Sustainable Development Goals (Barona et al., 2023). The study found that ports are developing circular

TABLE 1 Types of recycled waste of selected seaports from literature review.

Seaport	Type of waste	Source
Szczecin	Biomass	(Mańkowska et al., 2021)
Port of Antwerp	High-grade material fractions from construction and demolition: e.g. gypsum, aluminum, plastic, wood, calorific waste (insulation), autoclaved aerated concentrate (AAC), organic materials, metals, concentrate, cement-bound products, acid-soluble sulfate	(Bergmans et al., 2015)
Haiphong ports, Vietnam	Food waste, glass, paper and cardboard, plastics (e.g., packaging, bottles), metal (e.g., cans), clothes, rags, other (e.g., wood, rubber)	(To and Kato, 2017)
Benoa–Bali Indonesia, the public seaport and fishing terminal Benoa Maritime Tourism Hub (BMTH)	Fishbone can be turned into handicrafts for travel souvenirs or calcium supplements, organic garbage can be sent to a composting facility, another recyclable product can be used to generate renewable energy and solid squid waste can be turned into collagen, melanin, chitin, or biodiesel.	(Ferreira et al., 2022)
Asyaport, Marport and Port Akdeniz from Turkey Rotterdam and Hamburg Port from Europe Port of San Diego and Port of Long Beach from the USA	Recycle everything, e.g. plastic (bottles), paper (newspapers, magazines), tires, computers	(Satir and Doğan-Sağlamtimur, 2028)
Australian ports	Metal (64%), paper (27%), plastic (5%), tires, glass and other	(Du et al., 2023)
Port of Amsterdam	Food waste and wastewater to produce biogas, electricity, fertilizer and stream, bioglycerine, lasso waste into aromatics (for chemical companies), recycle biomass (peel of potatoes) to fatty acids	(de Langen and Sornn-Friese, 2019)
Port of Rotterdam	Waste to chemicals, biodiesel, methanol from wood pellets	
Port of Moerdijk	Biowaste to electricity, e-scrap from Europe, pyrolysis to extract products from waste: pallets, plastic foils, sewage sludge, and tires	
Port of Groningen	The biorefinery processes biowaste, while paint and coating companies use wood chips and other second-generation biomass as chemical industry ingredients. Polluted steel scrap containing asbestos is recycled into advanced raw materials for the steel industry, and asbestos fibers break down into sand, glass, and magnesia.	
Zeeland Seaports	Biowaste	
Northwest Russian seaports (Vyborg, St.Petersburg, Ust-Luga, Leningrad oblast)	Biomass	(Proskurina et al., 2016)
Antwerp and Koper Ports	Recycled plastic waste, biowaste, recycled goods used	(Kovačič Lukman et al., 2022)
Port Klang (Malaysia)	Recycling textile waste	(Ahmad et al., 2016)
Copenhagen-MalmöPort (CMP)	Biodegradable waste to biogas	(Karimpour et al., 2019)

practices and business models for technical and biological flows, but the level of implementation is moderate to low.

3 Data & methods

3.1 Characteristics of the ports under consideration

The subject of the analysis are Polish seaports handling CSC cargo with an average turnover of at least 100,000 tonnes in the last 10 years. These are ports of fundamental importance to the economy, i.e.: Gdańsk, Gdynia, Szczecin, and Świnoujście handling more than 10 million tonnes per year, as well as medium-size Polish ports of regional or local importance: Kołobrzeg and Darłowo, whose transshipments range from 100-300 thousand tonnes. The location of the studied ports on the Polish coast is shown in Figure 1. Table 3 shows the transshipments in 2011-2022.

3.2 Methods

To answer the first research question *What types of cargo occurring in seaports can be classified as CSC cargo?* An analysis of the literature and European Commission programs on the development of the CE was carried out (European Commission, 2020) as well as European Union and national legislation on waste management. Based on these, the loads occurring in seaports were identified, which were further subjected to statistical analysis and qualitative research.

To determine for which ports CSC cargo may be an important area of port activity (Research Question 2), the relationship between

TABLE 2 The circular economy in seaport – practical influence from literature review.

ID	Seaport	About circular economy in seaport	Circular economy's practical influence	Source
1	Port authorities in 26 countries participated in the study.	In seaports, the implementation of circular economy principles can result in a positive feedback loop of sustainable development by boosting local benefits, mitigating adverse effects, and promoting cooperation between ports and cities.	By implementing the concepts of the circular economy, ports can enhance local advantages. For collaboration framework is suggested so that cities and ports can implement the circular economy. By using the concepts of the circular economy, ports can assist the local populace economically. A survey on adoption and obstacles was conducted among port authorities in 26 countries. Extra financial advantages for nearby cities. Decrease in the adverse effects of port operations.	(Roberts et al., 2021)
2	Port of Amsterdam's	As demonstrated in the Port of Amsterdam case study, the circular economy transition affects seaports by changing the business models of port authorities, establishing ecosystems for the circular economy, and encouraging company synergies.	The evaluation of the circular economy's effects on port development firms. It provides a framework for examining how the circular economy may affect port authorities' business model. The central idea is the Port of Amsterdam's contribution to the creation of a circular economy. The circular economy transition has an impact on the port business ecosystem. There have been changes noted to the port development businesses' business models.	(de Langen et al., 2020)
3	Rotterdam Port (Havenbedrijf Rotterdam NV)	To improve economic growth and foster a more harmonious and effective connection, the circular economy has an impact on seaports by encouraging integration, sustainability, and regeneration of port-city districts.	Authorities from the port and the city work together for sustainability and circularity. Economic diversification for increased resilience and better environmental outcomes. Integrating ports and cities to promote circularity and sustainable cohabitation. The Makers District in Rotterdam serves as an example of urban renewal. The oil industry's spatial effects on the port landscape of Rotterdam Reusing a warehouse at Rotterdam Port for innovative businesses.	(de Martino, 2022)
4	Benoa in Indonesia	The application of the circular economy at seaports—such as Benoa, Indonesia—can improve sustainability through the integration of waste management into various port operations, resulting in the production of new energy and the effective use of resources.	Combining public and fishing ports for sustainable development. Processing fisheries products and managing waste in an effective and profitable manner. Conversion of the port and fishing industries to value-driven systems. Emphasize green port operations for sustainable development. Beneficial impacts on energy production and management of waste. The sustainability of the port ecosystem benefits from the circular economy.	(Ferreira et al., 2022)
5	Copenhagen-Malmö Port (CMP)	Circular economy models, such as waste-to-clean energy, improve seaport sustainability by reducing waste, using biogas plants, and employing cold ironing, as proven in the Copenhagen-Malmö Port case study.	Waste-to-clean energy model implementation in port cities. The circular economy model's viability for waste management. Copenhagen and Malmö Port, emphasize the circular economy for long-term viability. Examines a waste-to-clean energy model to determine the self-sustainability of ports.	(Karimpour et al., 2019)
6	Antwerp and Koper Ports	The circular economy has an impact on seaports by encouraging sustainability, offering insights into circular operations within ports, and assessing circularity using metrics such as the 9 R-strategy transitions.	Assess the effectiveness of seaports' transformation to a circular economy. Determine the seaports' areas of weakness and potential for growth.	(Kovačič Lukman et al., 2022)

(Continued)

TABLE 2 Continued

ID	Seaport	About circular economy in seaport	Circular economy's practical influence	Source
			Presents a model for measuring the acceleration of the circular economy at seaports.	
7	Rotterdam, Ningbo, Port Said Region, Al Ismailia Region and Suez Region	The circular economy concept addresses environmental and social issues while fostering eco-friendly behaviors, resource efficiency, and economic growth, all of which contribute to sustainable development in seaport cities.	Implementing the circular economy paradigm to promote sustainable growth. Implementing the circular economy in the Suez Canal Corridor Project presents challenges. For sustainable growth, seaport cities should prioritize the circular economy. Examine the consequences of the Suez Canal Corridor Project for sustainability.	(Ezzat, 2016)
8	Five Belgian seaports: Antwerp, Zeebrugge, Ghent, Oostende, Brussels	The influence of the circular economy on seaports is demonstrated by the transition patterns of Belgian ports, which prioritize energy recovery above sustainable efforts. However, there is still opportunity to improve cargo arranging roles and introduce new business models.	Ports' degrees of maturity in the circular economy differ. Neglecting the significance of cargo orchestration during the shift. Circular economy maturity levels and transition patterns of Belgian seaports are examined. Emphasis on energy recovery and the dearth of eco-friendly projects were noted.	(Haezendonck and Van Den Berghe, 2020)
9	Zeeland Seaports, Port of Amsterdam, Port of Rotterdam, Port of Moerdijk, Port of Groningen	Seaport operations are faced with both possibilities and challenges as a result of the circular economy, which makes them relevant for end-of-life activities including reusing, remanufacturing, and recycling.	The move to a circular economy presents both risks and possibilities for ports. Circular economy activities can reshape the competitive landscape between ports. The transition to circular economy has ramifications for seaports. Ports are suitable places for circular economy activity.	(de Langen and Sornn-Friese, 2019)
10	Szczecin	Circular economy models have the potential to turn secondary ports into sustainable nodes of circular supply chains, creating possibilities for growth while also needing effort to solve constraints such as infrastructure, coordination, and cultural adjustments.	Establish guidelines for investor evaluations in order to promote investments in circular supply chains. Create all-inclusive service offerings and collaborate with the many players in the circular supply chain. For sustainability, pay particular attention to secondary ports in circular supply chains. Determines the tasks, obstacles, and prospects for secondary ports.	(Mańkowska et al., 2021)

the size of the port, measured by the average turnover of cargo handled at the studied port (TT) in 2012-2022, and the average share of CSC cargo in total cargo handling (CET) was analyzed according to the formula:

$$CET = f(TT)$$

The individual indicators for the ports analyzed were as follows (Table 4):

The main data sources were data obtained from the Eurostat Database as well as transshipment statistics obtained directly from the ports surveyed. The results were presented in graphical form, based on which a trend function was determined.

To answer the second research question *What factors determine the choice of a particular port for handling CSC cargo?* Face-to-face interviews were conducted. In the case of ports generating less cargo handling (A, B), these were representatives of the entities managing these ports. For the other ports (C, D, E, F), representatives of handling and storage companies. The characteristics of the entities surveyed are shown in Table 5.

Eight interviews were conducted, the duration of which ranged from 0.5 to 1.5 hours. The average interview duration was 1 h 11 min. The location of the interview depended on the location of the port (Table 5), these were the following locations: Kołobrzeg, Darłowo, Gdynia, Gdańsk, Świnoujście, Szczecin. All respondents were men. The selection of respondents was purposeful due to their competencies and knowledge in the field of transshipment and storage of CSC cargo. In smaller ports (Darłowo, Kołobrzeg), port authorities, in addition to their management functions, directly create the directions of operational activity. In the remaining ports, the selection of entities resulted from the scope of their professional competencies.

In the next step, the identified factors were classified and prioritized and, based on these, actions (managerial implications) were proposed to be taken to intensify CSC cargo handling in seaports.

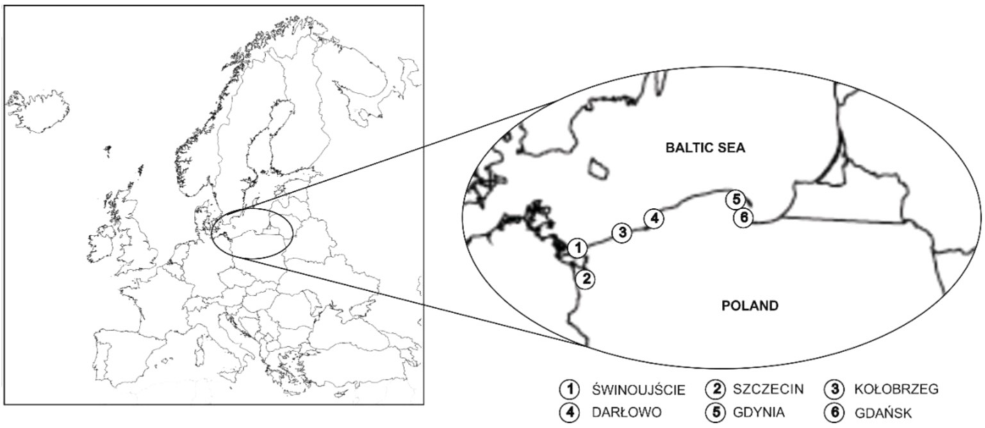

FIGURE 1
Location of ports surveyed.

4 Results

4.1 Identification of CSC cargo handled in seaports

The circular economy is an economic system designed to maximize the use of resources and generate a minimum amount of waste for disposal (Deutz, 2020).

In March 2020, the European Commission unveiled the fresh Circular Economy Action Plan (CEAP). CE primarily, but not exclusively policy objective is to reduce waste. Actions focus on the sectors that use the most resources and where the potential for circularity is high such as electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water, and nutrients.

According to the above definition, CE's sphere of interest is primarily waste. However, many researchers include by-products in this group (Batista et al., 2018; Lavelli, 2021; Dervojeda et al., 2014) which arise because of production and are not the main purpose of production. In practice, CSC cargo can be divided into:

- consumer waste
- production: waste and by-products (understood as substances created as a result of a production process whose primary purpose is not its production) (Figure 2).

The division of CE loads is a consequence of the classification of CE supply chains presented in the literature (and the chains owe their names to the "generators" of loads). A similar classification system of loads in the circular supply chain is presented in research (Mańkowska et al., 2020). This classification is important because it provides tools for better management of resource flows in the economy, supporting the goals of sustainable development and the circular economy, by increasing the efficiency of raw material use. There are as many as 5 premises that justify the above classification:

1. Identification of resource flows - allows for the recognition of how resources flow in the consumption and production phases through the economic system, making it easier to identify where waste is generated.
2. Optimization of production processes - waste is generated in the consumption process, but also in production. It was identified that there is a "by-product" category, which allows entities to better optimize their processes. By-

TABLE 3 Total transshipments from 2012 to 2022 of the studied ports.

Ports	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Total transshipments												
Kolobrzeg	259	301	129	151	115	140	211	280	246	131	174	170
Darlowo	80	157	108	117	332	91	107	254	213	143	139	92
Gdynia	12 992	13 187	15 051	16 961	15 391	17 751	18 378	20 774	20 548	21 220	22 745	23 075
Gdansk	23 513	24 379	27 335	28 771	31 685	31 566	33 940	42 438	45 522	40 575	45 020	63 153
Świnoujście	10 680	11 280	12 024	12 468	11 759	12 573	14 709	16 807	15 936	15 097	17 167	19 998
Szczecin	8 064	7 590	7 886	8 156	8 276	8 911	8 743	9 362	9 582	9 581	9 905	11 209

TABLE 4 TT and CET indicators for the ports surveyed (thousand tonnes).

port	*TT*	*CET*
Kolobrzeg	192	16%
Darlowo	153	24%
Gdynia	18173	10%
Gdansk	36491	2%
Świnoujście	14208	2%
Szczecin	8939	10%

products can be reused, which allows for minimizing raw material losses and increasing production efficiency.

3. Support for the idea of a circular economy - this classification indicates that there is a division into waste and by-products. This means that not all products withdrawn from the main process are useless. By-products can find new applications in other production processes, which is consistent with the idea of a closed life cycle of products/materials/raw materials.
4. Waste management - the above classification provides the basis for effective management of various types of waste, by distinguishing them between those that are created in the consumption process and those that are the result of the production process. Thanks to this, sustainable recycling and reuse systems can be created more effectively.
5. Responsible monitoring and reporting - this classification provides a premise for precise monitoring of processes related to the circular economy and contributes to transparent reporting of the impact of consumption and production processes on the environment. Thanks to the conclusions drawn from monitoring and reporting, decision-makers can create appropriate regulations and strategies focused on sustainable development.

The essence of the Circular Economy idea is to find a use for waste so that they de facto become by-products. And their use in production processes becomes profitable. One of the factors that has a significant impact on production costs is the transport of raw materials. For this reason, sea transport, due to its mass and unit cost of transport, is most predestined for handling low-value CE cargo.

The subject of the research described in this article are all CSC cargo that can constitute cargo in a seaport. While the classification of consumer waste is relatively straightforward (e.g. tires or scrap metal), it is not so straightforward in the case of production residues. In the European Union, there are regulations in place to identify and classify waste (Commission Decision, 2014) covering both used consumer products (e.g. tires, vehicles) and by-products of production processes (*e.g. waste from mineral extraction, waste from agriculture, or waste from the iron and steel industry), which can be further processed and used. However, not every by-product resulting from a production process is waste. If an object or substance resulting from a production process fulfills certain conditions, e.g. it is safe for the environment and human life and health, its use is certain without further processing, it can be considered a product and be placed on the market (Dz.U.2023.1587). It is therefore difficult to assess which of the loads subject to this analysis is a by-product and which is waste.

TABLE 5 Synthetic characteristics of respondents surveyed.

Terminal operator	Location (port)	Main cargo handled	CSC* cargo type	Number of respondents	Respondents (position)	Gender	Interview duration (h)
A	Kolobrzeg	dry bulk, wood	biomass, sharps	1	President of the Port Authority	male	1,5
B	Darlowo	dry bulk	ashes, wheat bran, scrap metal	1	Port Authority Harbour Operations Inspector	male	1
C	Gdynia	container and ferry general cargo, dry bulk cargo	sharps, scrap, UPS	1	Chairman of the board of one of the transshipment companies	male	1,5
D	Gdansk	containerized general cargo, crude oil, dry bulk	scrap metal, UPS, biomass	2	1. CEO of one of the handling companies; 2. Owner of a scrap metal handling terminal	male male	1,5 0,5
E	Świnoujście	general cargo, LNG, dry bulk	sharps, biomass	1	Logistics director of one of the transshipment companies	male	1
F	Szczecin	dry bulk, conventional general cargo	Sulphuric acid, UPS, used car tires, biomass, sharps, pulp, sulfite lye	2	1. Vice President of one of the transshipment companies, Logistics 2. Director of one of the transshipment companies	male male	1,5 1

*CSC charges referred to by respondents.

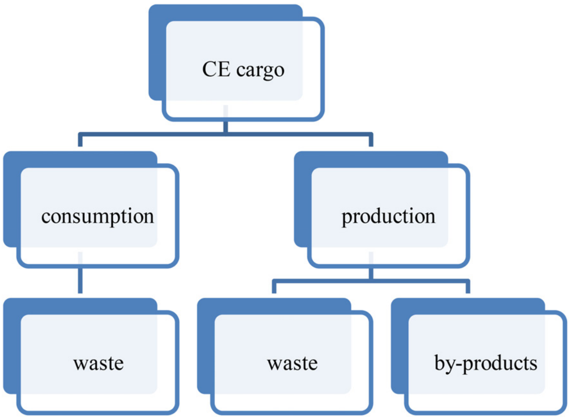

FIGURE 2
Circular Economy cargo.

For the purpose of the study, the analysis considers those cargo handled in seaports that can be assigned a waste code according to EU regulations (Table 6).

Considering sectors with potential for circularity, these are loads for:

- food sector: expellers, pulp, middlings, oilcakes, wheat bran,
- chemical and construction sectors: sulphuric acid, gypsum, ash, coal tar, glass cullet, slag, post-sulfite lye,
- energy sector: biomass
- steel sector: scrap metal.

TABLE 6 Cargo handled in seaports subject to CE survey.

	code	description
Biomass	03 01 05	Sawdust, shavings, cuttings, wood, particle board, and veneer other than those mentioned in 03 01 04
Expellers	02 03 03	Post-extraction waste
Gypsum	10 02 13*	Sludges and filter cakes from waste gas treatment containing dangerous substances
Sulphuric acid	10 01 09	Sulphuric acid
Post-sulphite lye	03 03 02	Sludges and slurries from sulfite pulp production (including green liquor sludge)
Oilcake	02 03 03	Post-extraction waste
Wheat bran	02 03 01	Sludges from washing, cleaning, peeling, centrifuging, and separation of raw materials
Ash	10 01	Wastes from power stations and other combustion plants
Coal tar	17 03 03*	Tar and tar products
Glass cullet	10 11 12	Waste glass other than those mentioned in 10 11 11
Shots	02 03 03	Post-extraction waste
pulp	02 04 80	Pulp
Scrap	17 04	Metallic and metal alloy wastes and scrap
Cinder	19 01 12	Slags and bottom ash other than those mentioned in 19 01 11

Source: Commission Decision 2014/955/EU.

The cargo analyzed vary greatly in value. There are products whose price does not exceed a few tens of EUR/tonne, e.g. slag, glass cullet orash. There are also products with a very high value exceeding EUR 1,000/tonne, e.g. stainless steel scrap or copper scrap. Approximate market prices of the surveyed cargo are shown in (Table 7) (as of September 2023 in Poland).

4.2 Analysis of CE cargo handling in the seaports studied

Ports of primary importance handle the largest volume of CSC cargo; however, these are largely agro cargo i.e. soybean meal or rapeseed, which are high-value animal feed and thus cargo desired to be handled by seaports. In the case of smaller ports, i.e. Kołobrzeg and Darłowo, these are much less valuable cargo, mainly biomass pellets and ashes (Table 8).

The analysis of transshipments and shares of CSC cargo in total handling in seaports showed that such cargo have a different impact on the studied ports. They have the greatest impact on reloading for smaller ports, i.e. Darłowo and Kołobrzeg. Their share in reloading reached as much as 35% in Kołobrzeg (2015) and 58% in Darłowo (2021). (Figure 3), while for ports of primary importance, their share did not exceed 15%.

An analysis of the relationship between the port's total cargo volumes and the share of CSC cargo clearly shows a logarithmic relationship. The smaller the port's total transshipments, the more significant the CSC share. This relationship is shown in Figure 4.

This leads to the conclusion that it is the ports with lower total cargo handling, which have been most affected by economic and political changes that benefit the most from CSC cargo handling. In the era of changes resulting from climate policy and economic shocks (e.g. COVID-19, Ukraine war), secondary ports are

TABLE 7 Average unit value of selected waste in Poland by type of material and partner (Extra-EU27 (from 2020) and Intra-EU27 (from 2020)).

Items		Extra-EU27 (from 2020)	Extra-EU27 (from 2020)	Intra-EU27 (from 2020)	Intra-EU27 (from 2020)
		imports	exports	imports	exports
Rubber	euro/tonne	587.45	246.49	444.74	339.02
Wood	euro/tonne	147.52	320.73	115.38	229.30
Glass	euro/tonne	446.67	75.36	38.55	67.38
Organic - vegetal origin	euro/tonne	587.76	561.73	236.28	209.05
Mineral	euro/tonne	4 029.88	37.59	316.33	201.75
Metal	euro/tonne	4 247.52	818.35	1 581.96	1 227.95
Metal - ferrous	euro/tonne	574.25	415.99	435.20	594.95
Metal - non ferrous	euro/tonne	6 199.75	9 056.46	3 662.59	3 414.85
Not specified	euro/tonne	674.39	616.31	523.64	677.49

Source: own calculations based on (Eurostat Trade in Waste…).

replacing the decreasing transshipment of traditional cargoes such as coal or iron ore with growing transshipments of circular economy cargo.

4.3 Identification of factors determining the choice of a port for handling CSC cargo

Qualitative research - face-to-face interviews - was conducted to identify the factors that determine the choice of a port as a link in the reverse supply chain. The results of the research are presented in Table 9.

Identification of the factors that determined the choice of a particular port by a gestor and the frequency of their occurrence made it possible to hierarchize them (Figure 5). The most common factor was the location of the port close to the place of production of the CSC cargo in question or its destination. This is most often due to the low value of the cargo and thus the need to minimize transport costs, in which back-end transport costs make up a significant part. Furthermore, it is a factor that is independent of the size of the port and therefore favors regional/local ports. The second most important factor is port flexibility. A port operator that is open to handling small batches of cargo with different handling and storage requirements, and often small and variable over time, is appreciated by cargo operators. This factor is not dependent on the size of the port.

In four cases, the choice of port was determined by infrastructural factors, including twice the importance of the parameters of the ships to be handled and twice the importance of adequate hinterland transport. In both cases, there is little that both terminals and ports can do. Transport accessibility of the port from the hinterland and foreshore is within the scope of the state's transport policy being implemented. In three cases, the choice of the port was determined by the operation of a dedicated terminal on the site, most often under the responsibility of one of the global traders of the cargo in question (middlings). The next most important factors, i.e.: terminal infrastructure - storage area, terminal know-how, port flexibility - are factors dependent on the port and/or terminal itself, its willingness to adapt to changing economic conditions, and not on the size of the port itself. Similarly, land reserves or the convenient location of the terminal in the port are also not necessarily related to the size of the port but can be an important factor in the development of ports with low overall cargo handling. The last factor identified - the developed industrial

TABLE 8 CSC cargo transshipments between 2012 and 2022 of the ports surveyed (thousand tonnes).

Ports	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Kolobrzeg	44	26	41	37	40	29	30	22	21	27	34	29
Darlowo	0	0	9	18	32	28	41	48	56	80	81	52
Gdynia	1 336	1 102	1 143	1 088	1 307	1 791	2 012	2 052	2 019	2 340	2 260	2 455
Gdansk	914	1 148	1 143	1 203	888	402	360	472	726	854	989	568
Świnoujście	29	327	492	415	499	314	279	279	418	347	333	245
Szczecin	980	1 180	925	979	1 241	986	826	866	790	763	861	810

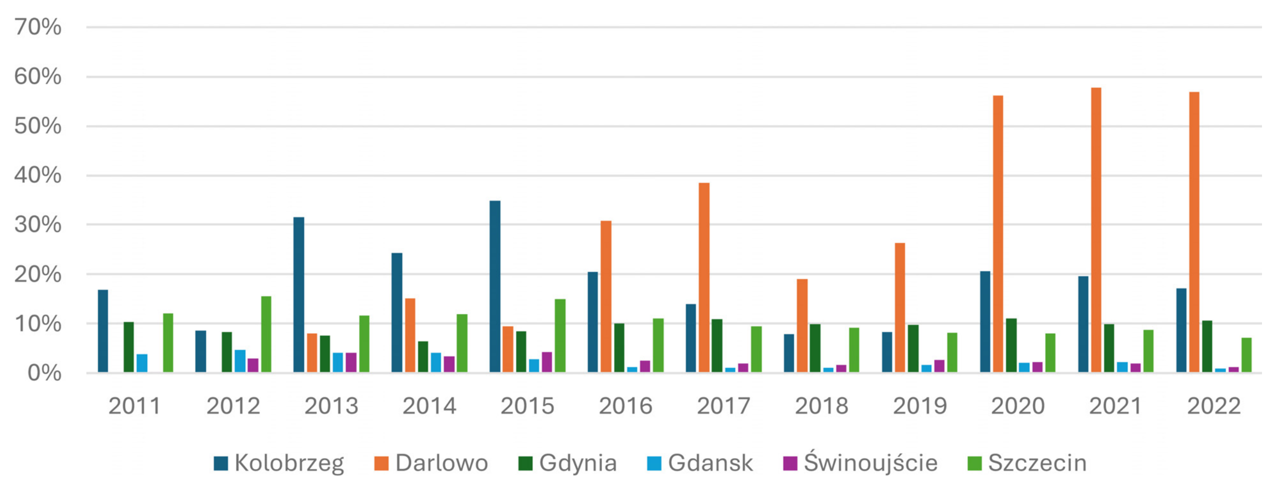

FIGURE 3
Share of CSC in transshipments between 2011 and 2022 in the studied ports.

function of the port - is more prevalent in large ports but is also, of all those identified, the least important.

5 Discussion

The results of this study provide valuable insights into the factors influencing the choice of ports for handling CSC cargo, specifically in the context of Polish seaports. The discussion will address the key findings, their implications, potential challenges, and future research directions.

The analysis revealed several critical factors that determine the selection of ports for CSC cargo handling. Among these, the size of the port, measured by the total transshipments (TT), and the share of CSC cargo in total cargo handling (CET) emerged as significant determinants. Larger ports such as Gdańsk and Gdynia, despite their higher transshipment volumes, exhibited a relatively lower share of CSC cargo. In contrast, smaller ports like Kołobrzeg and Darłowo had higher CET percentages, suggesting a more focused or specialized approach toward CE activities.

This divergence highlights the potential role of smaller ports in pioneering CE initiatives due to their ability to adapt more swiftly to new operational models. These ports can leverage their flexibility and regional significance to become specialized hubs for CE activities, potentially fostering local economic development and enhancing sustainability.

Furthermore, the qualitative analysis identified key factors influencing port choice for CSC cargo, including logistical efficiency, proximity to waste generation and recycling centers, availability of specialized facilities, and the presence of supportive regulatory frameworks. These factors underline the importance of an integrated approach where infrastructure, policy, and market dynamics align to support the circular economy.

Despite the promising findings, several challenges must be addressed to optimize port operations for CSC cargo:

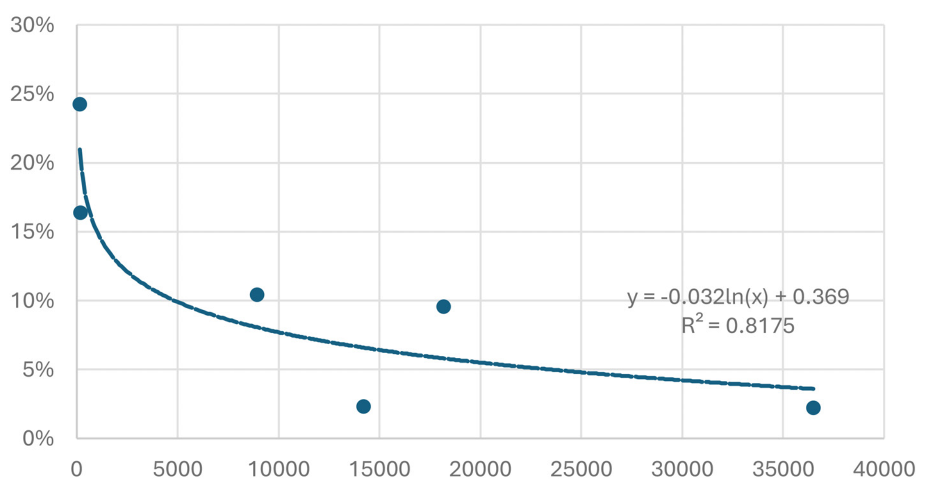

FIGURE 4
Relationship between port volume and share of CSC handling in total turnover.

TABLE 9 Factors determining the choice of a particular port as a link in reverse supply chains.

port	load	Port selection factors	description
Kolobrzeg	biomass	The convenient location of the terminal in the port Well-established business relationship	Developed logistic line via Kolobrzeg in relation to biomass supplier; no conflict with the tourist function of the city
Kolobrzeg	middlings, pulp	Transport accessibility - hinterland Terminal (s) flexibility	Rail connection of Kolobrzeg; opening of the port operator to low-volume cargo handling,
Darlowo	ashes	Port location	Location in the vicinity of the port of an entity importing ash as an ingredient in agricultural fertilizers
Darlowo	wheat bran	Port location Transport accessibility - ships parameters Transport accessibility - hinterland	Location of bran producer approx. 50 km from port, export to close Baltic markets not requiring large vessels
Darlowo	scrap	Terminal (s) flexibility	The operator operating in the port area has yards dedicated to scrap handling; once enough has been accumulated in the yards, transport by ship is arranged
Gdynia	sharps	Transport accessibility -ships parameters Terminal infrastructure - storage area	Depths in the port corresponding to the needs of vessels this cargo from America; developed storage capacity dedicated to sharps
Gdynia	scrap	Well-established business relationship	Cooperation with the port of a company belonging to one of the giants in the scrap metal trade -Liberty/GFG Alliance,
Gdynia Gdansk	ashes, gypsum Speedway	Port location Terminal know-how	Geographical proximity to a power plant producing ash as a by-product; experience of the port operator in handling UPS by-products of combustion) translating into handling UPS also from plants located further back.
Gdansk	scrap	Land reserves Port flexibility	The possibility of establishing one's own transhipment and storage terminal and arranging various forms of transport (conventional transport, container transport from and to Asia via DCT Gdansk)
Gdansk	biomass	Terminal know-how Terminal(s) flexibility Port location	The operator's experience in handling different types of biomass and gestors submitting both smaller and larger annual volumes for handling; geographical proximity to biomass co-firing plants
Świnoujście	sharps	Well-established business relationship Dedicated terminal	Within the port area, since 2012, the only terminal for handling and storing meal in Poland has been operating for the Bunge company - the largest in Poland and one of the largest in Central Europe processors of oilseeds and producer of vegetable fats
Świnoujście	biomass	Terminal infrastructure - storage area	The operator has warehouses prepared to handle biomass requiring indoor storage: pellets, marc, etc.; from the warehouses, it is possible to load onto cars, barges and wagons; hardened storage yards where it is possible to store biomass that is not sensitive to weather conditions, such as shells, woodchips, etc.
Szczecin	gypsum	Port location Terminal (s) flexibility	Geographical proximity to a power plant generating gos as post-production waste
Szczecin	biomass	Port location Terminal (s) flexibility	Proximity to potential customers - a biomass power plant is located in the port area, a biomass co-firing plant is located in the vicinity of the port; proximity to the gestors/traders in the vicinity of the port
Szczecin	sulphuric acid	Land reserves Port flexibility	The possibility of building its own distribution terminal for this cargo on the port site with a dedicated quay and the possibility of further expansion
Szczecin	car tyres	Developed industrial function of the port Port location	Location of three car tyre pyrolysis plants in the port area; cross-border location
Szczecin	sharps	Well-established business relationship Dedicated terminal	The largest terminal is owned by the large Vitter corporation
Szczecin	pulp	Dedicated terminal Port location	The operation of several agro terminals in the port area which can also handle dried, palletised pulp, the geographical proximity of one of the sugar mills

(Continued)

TABLE 9 Continued

port	load	Port selection factors	description
Szczecin	ashes, slag	Port location Terminal (s) flexibility	In exports, proximity to ash-as-waste plants; flexibility of port handling operators; in imports, proximity to ongoing road investments
Szczecin	post-sulfite lye	Port location Terminal (s) flexibility	Geographical proximity of the consignee to the port; successful cooperation of the consignee with the operator at the port in handling other cargo

Source: own research.

1. Infrastructure Limitations: Many ports, particularly the smaller ones, may lack the necessary infrastructure to handle diverse CSC cargo efficiently. Upgrading facilities to accommodate various types of recyclable and reusable materials is essential.
2. Coordination and Collaboration: Effective CE implementation requires robust coordination among multiple stakeholders, including port authorities, local governments, waste management companies, and logistics providers. Enhancing collaboration mechanisms is crucial to streamline operations and achieve CE goals.
3. Regulatory and Policy Support: The success of CE initiatives heavily relies on supportive regulatory frameworks. Policymakers must create conducive environments through incentives, standards, and regulations that encourage sustainable practices within ports.
4. Market Dynamics: The economic viability of CE activities is influenced by market demand for recycled and upcycled materials. Developing strong markets for CE products is necessary to sustain and scale port-based CE operations.

5.1 Future research directions

Building upon the findings of this study, several avenues for future research are proposed to deepen the understanding of the role of ports in advancing the circular economy (CE):

5.1.1 Comparative analyses

A cross-national or regional comparative study of port operations would be valuable for identifying best practices and innovative approaches in circular economy cargo handling. Such studies could highlight differences in policy, technology adoption, and stakeholder involvement that contribute to success in CE implementation.

5.1.2 Technological advancements

The role of emerging technologies, including blockchain, the Internet of Things (IoT), and artificial intelligence (AI), should be further examined in the context of optimizing logistics and operations at ports. Research could focus on how these technologies improve transparency, traceability, and efficiency in CE practices within port ecosystems.

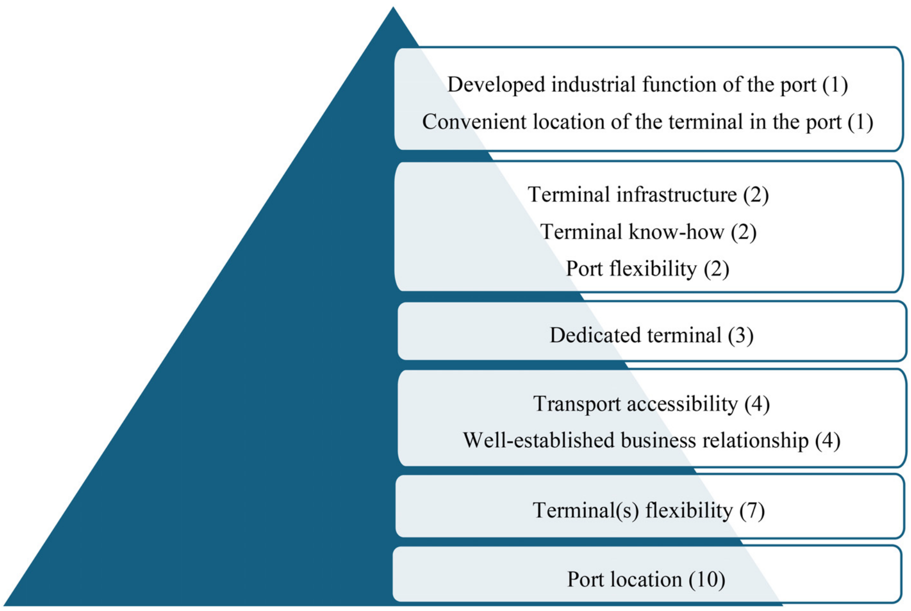

FIGURE 5
Hierarchy of determinants of port choice in CSC cargo handling. own research.

5.1.3 Economic impact studies

Future studies could focus on conducting a thorough economic impact analysis to evaluate the contribution of circular economy activities to local and regional economies. Quantifying these impacts would provide empirical support for increased investment in CE-related infrastructure at ports and across broader supply chains.

5.1.4 Stakeholder engagement and governance models

Developing and empirically testing new models of stakeholder engagement and governance will be critical to understanding how diverse actors—ranging from government authorities to private companies—can be effectively integrated into the circular economy framework at ports. These models should assess collaboration strategies that enhance CE implementation.

5.1.5 Sustainability metrics and performance indicators

There is a need to refine and expand sustainability metrics specific to port operations, enabling more accurate monitoring and reporting of circular economy performance. This would involve the development of tailored indicators that can better capture the unique environmental and operational aspects of ports contributing to CE.

6 Conclusions

The analyses carried out showed that CSC cargo could be an important area of activity for the pores. The research showed a relationship between port size and the share of CSC cargo in transshipments. This relationship was logarithmic; the smaller the port, the greater the importance of CSC cargo. This qualitative research in Polish coastal ports allowed the identification of the main factors determining the choice of a given port by cargo managers, the most important of which was the location of the port close to the origin/destination of the cargo, which is usually associated with its low value, and the flexibility of the terminal handling the cargo. Most of the identified factors were not dependent on the size of the port handling CSC cargo and more on the terminal/port's ability/willingness to adapt. A limiting factor for the development of small ports is insufficient transport accessibility from the hinterland as well as insufficient parameters of the vessels handled. Nevertheless, for a higher share of CSC cargo in seaport service, action must be taken at all levels of decision-making: public authorities, port boards and terminal operators. The final factor identified—*the developed industrial function of the port*—while more commonly observed in large-scale ports, is the least significant among those examined in this study.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: stat.gov.pl.

Author contributions

EC: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. IK: Writing – review & editing, Writing – original draft, Investigation, Methodology, Software. AO-J: Writing – review & editing, Writing – original draft. MP: Writing – review & editing, Writing – original draft, Project administration, Data curation, Conceptualization, Investigation. ES: Writing – review & editing, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Adamowicz, M., and Puszkarski, J. (2018). Legal aspects of sustainable development of seaports in Poland. *SHS Web Conf.* 57, 1001. doi: 10.1051/SHSCONF/20185701001

Ahmad, S. S., Mulyadi, I. M. M., Ibrahim, N., and Othman, A. R. (2016). The application of recycled textile and innovative spatial design strategies for a recycling centre exhibition space. *Proc. - Soc Behav. Sci.* 234, 525–535. doi: 10.1016/J.SBSPRO.2016.10.271

Alamoush, A. S., Ballini, F., and Ölçer, A. I. (2021). Revisiting port sustainability as a foundation for the implementation of the United Nations Sustainable Development Goals (UN SDGs). *J. Shipp. Trd.* 6, 19. doi: 10.1186/s41072-021-00101-6

(2014). "Commission decision of 18 December 2014 amending decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and the Council (Text with EEA relevance)," in *2014/955/EU*.

Barona, J., Ballini, F., and Canepa, M. (2023). Circular developments of maritime industrial ports in Europe: a semi-systematic review of the current situation. *J. shipp. trd.* 8, 25. doi: 10.1186/s41072-023-00153-w

Batista, L., Bourlakis, M., Smart, P., and Maull, R. (2018). In search of a circular supply chain archetype – a content-analysis-based literature review. *Prod. Plan. Control* 29, 438–451. doi: 10.1080/09537287.2017.1343502

Bergmans, J., Broos, K., Nielsen, P., Dierckx, P., Brijsse, Y., and Jacobs, K. (2015). "Recycling of construction and demolition waste: case study in the port of Antwerp," in *Proceedings of the ISWA conference 2015*, Antwerp; Zenodo: Antwerp.

Bjørnbet, M., Skaar, C., Fet, A., and Schulte, K. (2021). Circular economy in manufacturing companies: A review of case study literature. *J. Cleaner Production* 294, 126268. doi: 10.1016/J.JCLEPRO.2021.126268

Bocheński, T., Palmowski, T., and Studzieniecki, T. (2021). The development of major seaports in the context of national maritime policy. The case study of Poland. *Sustainability* 13, 12883. doi: 10.3390/SU132212883

Courtens, F. M., Haezendonck, E., Dooms, M., and Verbeke, A. (2023). Accelerating the circular economy transition process for gateway ports: the case of the Port of Zeebrugge. *Maritime Transport Res.* 4, 100088. doi: 10.1016/j.martra.2023.100088

de Langen, P., and Sornn-Friese, H. (2019). Ports and the circular economy. *Green Ports Inl. Seaside Sustain. Transp. Strateg*, 85–108. doi: 10.1016/B978-0-12-814054-3.00005-0

de Langen, P. W., Sornn-Friese, H., and Hallworth, J. (2020). The role of port development companies in transitioning the port business ecosystem; the case of port of Amsterdam's circular activities. *Sustainability* 12, 4397. doi: 10.3390/SU12114397

de Martino, P. (2022). Towards circular Port–City territories: rotterdam and the port back to the city. *Geoj. Libr.* 128, 161–171. doi: 10.1007/978-3-030-78536-9_10/FIGURES/2

Dervojeda, K., Verzijl, D., Rouwmaat, E., Probst, L., and Frideres, L. (2014). Clean technologies: circular supply chains. *Bus. Innov. Obs.* 30, 18.

Deutz, P. (2020). Circular economy. *Int. Encycl. Hum. Geogr. Second Ed.* 2, 193–201. doi: 10.1016/B978-0-08-102295-5.10630-4

Du, L., Zuo, J., O'Farrell, K., Chang, R., Zillante, G., and Li, L. (2023). Transnational recycling of Australian export waste: an exploratory study. *Resour. Conserv. Recycl.* 196, 107041. doi: 10.1016/J.RESCONREC.2023.107041

Dziennik Ustaw, D. (2023). 1587 t.j. Akt obowiązujący Wersja od: 28 października 2023 r. do: 31 grudnia 2024 r. USTAWA z dnia 14 grudnia 2012 r. o odpadach. Dz.U.2023.1587.

European Commission (2020). *Communication from the Commission to the European Parliament, The Council, the European Economic And Social Committee and the Committee Of The Regions, A New Circular Economy Action Plan, for a Cleaner and More Competitive Europe COM(2020) 98 Final* (Brussels: European Commission).

Eurostat Trade in Waste *Type of Material and Partner*. Available online at: https://ec.europa.eu/eurostat/databrowser/product/page/ENV_WASTRDMP (Accessed 7 May 2024).

Ezzat, A. M. (2016). Sustainable development of seaport cities through circular economy: A comparative study with implications to suez canal corridor project. *Eur. J. Sustain. Dev.* 5, 509–522. doi: 10.14207/ejsd.2016.v5n4p509

Faut, L., Soyeur, F., Haezendonck, E., el Dooms, M., and de Langen, P. W. (2023). Ensuring circular strategy implementation: The development of circular economy indicators for ports. *Maritime Transport Res.* 4, 100087. doi: 10.1016/j.martra.2023.100087

Ferreira, J., Bek, D., Oloan, R., Gurning, S., and Tangkau, D. I. (2022). The analysis of the conceptual framework of green port implementation in Indonesia using circular economy: the case study of benoa public and fishing terminals. *Sustainability* 14, 6083. doi: 10.3390/SU14106083

Fredouet, C. H. (2023). *Identifying Maritime Ports' Investment Drivers: The Case of French Local and Regional Ports*, London, UK Vol. 2. 1–5. doi: 10.24018/maritime.2023.2.1.14

Geissdoerfer, M., Pieroni, M., Pigosso, D., and Soufani, K. (2020). Circular business models: A review. *SRPN: Soc. Economics (Topic)* 277, 123741. doi: 10.1016/j.jclepro.2020.123741

Haezendonck, E., and Van Den Berghe, K. (2020). Patterns of circular transition: what is the circular economy maturity of Belgian ports? *Sustainability* 12, 9269. doi: 10.3390/SU12219269

Jeevan, J., Mohd Salleh, N. H., Abdul Karim, N. H., and Cullinane, K. (2023). An environmental management system in seaports: evidence from Malaysia. *Marit. Policy Manage.* 50, 1118–1135. doi: 10.1080/03088839.2022.2047814

Karimpour, R., Ballini, F., and Ölcer, A. I. (2019). Circular economy approach to facilitate the transition of the port cities into self-sustainable energy ports—a case study in Copenhagen-Malmö Port (CMP). *WMU J. Marit. Aff.* 18, 225–247. doi: 10.1007/S13437-019-00170-2

Khan, S., and Haleem, A. (2021). Investigation of circular economy practices in the context of emerging economies: a CoCoSo approach. *Int. J. Sustain. Eng.* 14, 357–367. doi: 10.1080/19397038.2020.1871442

Kovačič Lukman, R., Brglez, K., and Krajnc, D. (20222022). A conceptual model for measuring a circular economy of seaports: A case study on Antwerp and Koper ports. *Sustainability* 14, 3467. doi: 10.3390/SU14063467

Lavelli, V. (2021). Circular food supply chains – impact on value addition and safety. *Trends Food Sci. Technol.* 114, 323–332. doi: 10.1016/J.TIFS.2021.06.008

Mańkowska, M., Kotowska, I., and Pluciński, M. (20202020). Seaports as nodal points of circular supply chains: opportunities and challenges for secondary ports. *Sustainability* 12, 3926. doi: 10.3390/SU12093926

Mańkowska, M., Pluciński, M., and Kotowska, I. (2021). Biomass sea-based supply chains and the secondary ports in the era of decarbonization. *Energies* 14, 1796. doi: 10.3390/EN14071796

McCallum, P. (2022). "Green ports—Sustainable port development," in *Ports 2022: Ports 2022: Port Planning and Development*, eds P. J. Erbland and B. N. Jones, Pap. from Sess. 16th Trienn. Int. Conf. Vol. 2, 592–600. doi: 10.1061/9780784484401.059

Mhatre, P., Panchal, R., Singh, A., and Bibyan, S. (2021). A systematic literature review on the circular economy initiatives in the European Union. *Sustain. Production Consumption* 26, 187–202. doi: 10.1016/J.SPC.2020.09.008

Michalska-Szajer, A., Klimek, H., and Dąbrowski, J. (2021). A comparative analysis of CSR disclosure of polish and selected foreign seaports. *Case Stud. Transp. Policy* 9, 1112–1121. doi: 10.1016/J.CSTP.2021.05.012

Oniszczuk-Jastrząbek, A., Pawłowska, B., and Czermański, E. (2018). Polish sea ports and the green port concept. *SHS Web Conf.* 57, 1023. doi: 10.1051/SHSCONF/20185701023

Padilla-Rivera, A., Russo-Garrido, S., and Merveille, N. (2020). Addressing the social aspects of a circular economy: A systematic literature review. *Sustainability* 12, 7912. doi: 10.3390/su12197912

Popović, A., and Radivojevic, V. (2022). The circular economy: Principles, strategies and goals. *Economics Sustain. Dev.* 6, 45–56. doi: 10.5937/esd2201045p

Proskurina, S., Rimppi, H., Heinimö, J., Hansson, J., Orlov, A., Raghu, K., et al. (2016). Logistical, economic, environmental and regulatory conditions for future wood pellet transportation by sea to europe: the case of northwest Russian seaports. *Renew. Sustain. Energy Rev.* 56, 38–50. doi: 10.1016/J.RSER.2015.11.030

Roberts, T., Williams, I., Preston, J., Clarke, N., Odum, M., and O'Gorman, S. (2021). A virtuous circle? Increasing local benefits from ports by adopting circular economy principles. *Sustain.* 13, 7079–7079. doi: 10.3390/su13137079

Sacco, S., and Cerreta, M. (2022). "A decision-making process for circular development of City-Port ecosystem: the East Naples case study," in *Computational Science and Its Applications – ICCSA 2022 Workshops. ICCSA 2022. Lecture Notes in Computer Science*. vol 13378. eds O. Gervasi, B. Murgante, A. M. A. C. Misra and Rocha. C. Garau. (Springer: Cham). doi: 10.1007/978-3-031-10562-3_40

Satir, T., and Doğan-Sağlamtimur, N. (2028). The protection of marine aquatic life: green port (EcoPort) model inspired by green port concept in selected ports from Turkey, Europe and the USA. *Period. Eng. Nat. Sci.* 6, 120–129. doi: 10.21533/PEN.V6I1.149

To, N. T., and Kato, T. (2017). Solid waste generated from ships: A case study on ship-waste composition and garbage delivery attitudes at haiphong ports, Vietnam. *J. Mater. Cycles Waste Manage.* 19, 988–998. doi: 10.1007/S10163-016-0466-3/TABLES/11