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Implementing Circular Economy in Seaports: Theory and Practice

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Karolina Gwarda[1], Adrianna Karaś[2]

Abstract:

Purpose: *This article aims to analyse and compare the implementation of circular economy (CE) solutions in three leading seaports of North-West Europe—Rotterdam, Antwerp-Bruges, and Hamburg—and to identify the key factors that determine the effectiveness of circular strategies in large industrial port ecosystems.*
Design/Methodology/Approach: *The study adopts a benchmarking approach based on a comparative analysis of CE initiatives implemented in the selected ports. The analysis covers strategic, infrastructural, and operational dimensions of circularity, focusing on waste management, industrial symbiosis, renewable energy deployment, water reuse, and technological innovation. Data were collected from port strategies, sustainability reports, and international sectoral databases.*
Findings: *The results reveal significant differences in the maturity of CE initiatives across the analysed ports. Antwerp-Bruges and Rotterdam demonstrate highly advanced solutions in industrial symbiosis, energy recovery, and the development of large-scale circular industrial districts, whereas Hamburg shows strong progress in technological innovation and decarbonisation-oriented projects.*
Practical Implications: *Although the beneficial reuse of dredged material is currently the most developed CE area among European ports, industrial symbiosis and heat reuse remain in the early stages in most cases. Across all ports, municipal and mixed waste streams represent an important yet still underutilised resource for circular processing.*
Originality/Value: *The findings underscore the need for more integrated waste-handling infrastructures, stronger cross-sectoral partnerships, and increased investment in technologies enabling reuse, recycling, and resource recovery. The benchmarking results may serve as a reference for other EU ports seeking to advance CE strategies and align with the EU Green Deal, Fit for 55, and CEAP requirements.*

Keywords: *Circular economy, seaport, benchmarking, sustainability development, innovations.*

JEL codes: *L91, O32, Q01, Q55, Q57.*
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[1]*Ph.D., Assistant Professor, Gdynia Maritime University, Faculty of Management & Quality Science, Gdynia, Poland, k.gwarda@wznj.umg.edu.pl;*
[2]*M.Sc., Gdynia Maritime University, Faculty of Management & Quality Science, Gdynia, Poland, a.karas@wznj.umg.edu.pl;*

1. Introduction

The transformation of the economy towards a circular economy (CE) model is currently one of the key priorities of European Union policy, particularly in the context of transport and port infrastructure (European Policy Centre, 2022). Seaports, as strategic logistics and industrial hubs, perform a dual function.

On the one hand, they generate significant streams of waste, resource consumption and emissions; on the other, owing to their scale, infrastructure and industrial linkages, they constitute ideal locations for establishing circular systems (Notteboom *et al.,* 2022).

Ports are a natural environment for implementing CE, and their role extends beyond infrastructure and logistics management. It also includes initiating and coordinating cooperation among companies, terminal operators, municipal units and the industrial sector (Notteboom *et al.,* 2022).

Effective CE implementation in port environments requires a new approach to resource management - one that entails not only waste reduction but also industrial symbiosis, the reuse of materials, the use of renewable energy and technological innovation (Barona *et al.,* 2023).

This article examines three of the largest ports in North-West Europe: Hamburg, Rotterdam and Antwerp. This choice is not accidental. These ports rank among the most significant in the region in terms of cargo throughput and economic importance, while simultaneously acting as pioneers in sustainable development strategies.

They run advanced programmes in the areas of renewable energy, emissions reduction, industrial symbiosis and resource recycling (Port of Antwerp-Bruges, 2023; Senatskanzlei Hamburg, 2023). In addition, they form highly industrialised ecosystems in which the circulation of materials and energy has considerable operational and economic potential, making them excellent examples for analysing CE implementation in practice.

The aim of the article is to present and compare CE initiatives in the three selected ports and to identify the factors determining the effectiveness of circular solutions in major seaports.

The analysis covers categories such as waste management, energy and infrastructure, transport, water management and technological innovation, while also identifying differences arising from local economic and institutional contexts.

The actions undertaken in the analysed ports may serve as an important point of reference for other EU ports that are implementing or planning to implement circular solutions in the maritime transport, logistics and industrial sectors.

2. Theoretical and Regulatory Framework of CE in Seaports

2.1 CE: Conceptual Foundations

The CE is not a new concept, although its dynamic development has occurred in recent years. Its origins date back to industrial ecology and the concept of industrial metabolism developed in the 1970s and 1980s, as well as the "cradle-to-cradle" approach and product life cycle analyses (Kirchherr *et al.,* 2023).

The CE represents a mode of organising economic activity that departs from traditional thinking about products in terms of their "end of life". At the centre of this approach are actions aimed at minimising waste generation by reducing resource consumption, reusing materials, recycling and recovering resources at the stages of production, distribution and use.

The concept operates on three levels: the micro level - encompassing firms, consumers and products; the meso level - relating, for example, to eco-industrial parks; and the macro level - referring to cities, regions or countries. Its overarching goal is to support sustainable development, understood as simultaneously strengthening environmental, economic and social well-being for present and future generations (Kirchherr *et al.,* 2017).

The CE constitutes an alternative to the dominant linear model based on the "take-make-use-dispose" scheme. The linear model overlooks the finiteness of resources and the environmental impacts associated with the generation of waste (Sauvé *et al.,* 2016).

In contrast, the circular model presupposes the creation of closed material and energy loops in which waste becomes secondary raw materials. The biological cycle includes renewable material streams, while the technical cycle refers to non-renewable materials which, through repair, refurbishment, reuse and recycling, can remain in circulation for as long as possible (Ellen MacArthur Foundation, 2015).

2.2 EU Policies Supporting CE in Seaports

The development of the CE in European seaports is strongly linked to EU policy, which establishes the regulatory and strategic frameworks for sectoral transformation. Key initiatives include the European Green Deal, the Fit for 55 legislative package, and the Circular Economy Action Plan (CEAP).

The European Green Deal provides the strategic foundation for the decarbonisation of ports. Under this strategy, the EU aims to achieve climate neutrality by 2050, which requires, among other measures, reducing emissions across all types of port activity, promoting alternative fuels, and increasing the energy efficiency of port infrastructure (Botana *et al.,* 2023).

The Fit for 55 package complements the Green Deal by introducing concrete regulations intended to reduce emissions in the maritime sector by at least 55% by 2030 compared to 1990 levels. In the port context, the most significant measures include the implementation of on-shore power supply (OPS) for vessels at berth, the inclusion of the maritime sector in the Emissions Trading System (ETS), and the increased share of renewable energy sources in the energy mix (Jacobs, 2022).

In parallel, the CEAP serves as a key instrument driving CE adoption in ports by promoting recycling, reuse, and the closing of material loops. According to the European Policy Centre report, ports may act as "circular hubs" - not only handling ship-generated waste but also initiating industrial symbiosis, developing eco-industrial parks, and implementing resource recovery systems (EPC, 2025).

In summary, EU policies provide robust frameworks that support the transition of ports towards a CE. The combination of climate regulations (Fit for 55), circularity-focused measures (CEAP), and strategic guidelines (Green Deal), reinforced by analysis and recommendations presented in the EPC report, creates opportunities for ports to transform into innovative and sustainable circular economy centres.

2.3 CE in Seaports

Seaports constitute key nodes in supply chains, and global maritime trade volumes continue to grow annually. According to the UNCTAD Review of Maritime Transport 2025, global maritime trade reached 12.720 million tons of cargo in 2024, representing an increase of 2.2% (UNCTAD, 2025).

The scale of cargo handling makes seaports some of the largest concentration points of flows, and increasing cargo volumes intensify port operations, resulting in higher energy consumption, increased demand for storage space, and rising amounts of waste and emissions from port activities.

This intensification necessitates redefining the role of seaports - from key nodes in land-sea supply chains to entities actively participating in sustainable development processes. In this context, the CE concept is gaining relevance as a practical tool for reducing the environmental impact of port activities while increasing resource efficiency (Skiba, 2024).

This trend is confirmed by the latest findings of the IAPH World Ports Tracker 2025, which indicate that circularity has become one of the key elements of sustainability strategies in the port sector. The report identifies four areas, yet the level of advancement in implementing circular initiatives varies significantly across them (IAPH World Ports Tracker, 2025):

1. Industrial symbiosis - 77% of ports reported no actions in this area, while only 14% have implemented operational solutions and 8% are in the design and

implementation phase. This indicates that although industrial symbiosis is perceived as a key component of port circularity, it remains in an early stage of development.

2. Beneficial use of dredged material - this is the most developed CE-related area. As many as 44% of ports have implemented operational activities and another 8% are in the implementation phase. Only 35% reported no actions. Dredged material is considered a valuable resource used in construction.
3. Heat reuse - only 17% of ports have reached the operational stage, while 74% have not undertaken any actions. This demonstrates that waste heat recovery remains largely underutilised.
4. Water reuse - 31% of ports conduct operational activities, while 18% are at earlier stages (8% initial, 4% design, 6% implementation). This highlights the growing importance of water management in port environmental strategies.
5. Beneficial use of waste streams - 29% of ports have implemented operational solutions, and 33% are at various planning and design stages, indicating that ports increasingly view waste not as an environmental burden but as a potential source of value.

The heterogeneity in the implementation of circular initiatives shows that although the CE concept is gaining recognition in the port environment, its full adoption requires a long-term approach, systemic changes and regulatory support due to the multi-dimensional role of seaports. As noted by Notteboom and Haralambides (2025), seaports are entities undergoing transformation not only at the digital and energy levels but also within the CE.

Meanwhile, research by Senarak (2025) indicates that the integration of circularity principles with digital technologies has gained prominence in recent years and can optimise logistics while reducing resource consumption. Nevertheless, despite rising awareness, the transition of seaports towards a circular economy model remains a complex process requiring consistent and coordinated actions.

3. Benchmarking Circular Economy Activities

The analysis of circular economy implementation in seaports requires examining the practices already being undertaken. This benchmarking study includes three European ports: Rotterdam, Antwerp-Bruges and Hamburg. The selection of these ports for comparative analysis stems from their leading role - in 2024, they collectively accounted for over 35% of container throughput among the 15 largest ports of the EU.

Rotterdam remains Europe's largest port, handling 13.82 million TEU, an increase of 2.8% compared to the previous year. Antwerp-Bruges ranks second with 13.53 million TEU and the highest growth rate among the top three - 8.1. Hamburg occupies third place, having handled 7.8 million TEU (Port Economics, 2025). Beyond operational scale, these ports are distinguished by extensive industrial hinterlands, advanced R&D ecosystems and proactive approaches to sustainability strategies.

Their significance makes them crucial examples for assessing the practical implementation of circular economy concepts.

Below is a detailed compilation of good practices identified in the Port of Rotterdam, Port of Antwerp-Bruges, and Port of Hamburg, categorised into key areas of circular activities.

Table 1. *CE in Seaports - examples, technologies and initiatives*

Circular Strategy	**Port of Rotterdam**	**Port of Anterp-Bruges**	**Port of Hamburg**
Decarbonization	• Neste – bio-diesel refinery • Routescanner • Shore-based power	• Antwerp@C: innovative CO2 reduction • Hydrotug: hydrogen-powered-tug • Methatug: methanol-powered tugboat	• SmartPort philosophy to achieve sustainable economic growth • Onshore power supply • Shore Power In European Shipping (SPIES)
Eco-project	• WasteShark aquadron • Holland Hydrogen 1	• Blue Line Logistics – inland shipping • Vacuum cleaning robot “Nul-O-Plastic” • PIONEERS project – PORTable Innovation Open Network for Efficiency and Emissions Reduction Solutions	• Feeder Barge – green logistics innovation
Incubator	• Nextlogic Platform • Start-up OBBOTEC: Selectieve Plastic Extractie (SPEX)	• BlueApp pre-incubator for sustainable chemistry and materials • Blue Chem Incubator for Sustainable Chemistry	• Hamburg homePort innovation platform and tech enabler • Clean Port & Logistics (CPL) • Project Port Innovators Network (PIN)
Industrial symbiosis	• Waste to Pure Raw Material • Green shore electric facility	• Ecluse steam network • Circular Water Use	• Sustainable Energy Hub Hamburg

	in Waalhaven • From Industrial Wastewater to Chlorine		
Port conscessions	• Project PORTHOS	• NextGen District Antwerp	
R1 – rethink	• Green and Digital Corridor • Charging station for electric trucks	• Flanders Ship Repair specialized in Repair and Industrial Maintenance	• Green Supply Chains – synergies in the electrification strategies • Skills for a Green Industrial Transition (GRIT) – education and training programme • Quantum inspired Traffic Light Control • smartWINDOW
R3 – reuse	• Thermal Cleaning of Tar-Bearing Asphalt	• Second Life project of geared container vessel • CHERISH2O project (CHEmical industry water Reuse In a Sustainable Harbour	
R4 – repair		• Engine Deck Repair Shipyard	
R5 - refurbish	• Wind-Assisted Propulsion systems refurbishment • Royal Roos retrofits ballast water filters and air lubrication systems	• Wind-Assisted Propulsion systems refurbishment	• Re-inventing Salzgitter Quay: Sustainability meets Coal
R6 – remanufacture		• TSR 'The Metal Company' recycles and remanufacures metals	• METHA – MEchanical Treatment and

			Dewatering of HArbour-sediments
R7 – repurpose	• Recycling of Wind Turbine Blades	• RecupBat and Febelauto give EV batteries a second life • TripleW develops waste–to-product solutions • Dismantled bridge from Zeebrugge repurposed as a jetty in port	
R8 – recycle	• Port Waste Profile Platform – geoFluxus • Recycling Lithum-lon batteries - TES	• Belgian Scrap Terminal • Cycling path made from recycled plastics • New West Gypsum Recycling specialized in plasterboard recycling	
R9 – recover	• Heat-distribution grid: Warmtelinq	• Antwerp North Heat Network	• Aurubis Hamburg – Waste Heat Supply to HafenCity
Redevelopment	• The Rotterdam Makers District for the innovative manufacturing industry	• Blue Gate Antwerp – sustainable business park • Conversion of former Fish Auction	• Grasbrook district
Spatial planning		• Kanaalkant appoints area manager	• HafenCity – revitalisation area • The 2040 Port Development Plan
Urban symbiosis		• Water-Kracht project for convert wastewater from Antwerp residents	• COMMON GROUND; social engagement through joint community days

Source: O*wn study based on: Circular Flanders; Port of Antwerp-Bruges, Port of Rotterdam, Port of Hamburg.*

4. Conclusions

The analysis of three major ports in North-West Europe - Rotterdam, Antwerp-Bruges, and Hamburg - demonstrates that the CE is becoming an important direction for the development of seaports. Despite differences in their economic structures and available resources, all these ports actively implement solutions that enable more efficient use of energy, water, and materials while reducing the amount of waste generated.

First, the most advanced ports have well-developed strategies and programmes for cooperation with businesses and academic institutions. This ensures that the implementation of new circular solutions is coherent and systematic.

Second, a key factor for success is modern infrastructure and well-developed systems for collecting, sorting and processing waste. Projects such as NextGen District or Porthos illustrate that ports invest both in technologies and in public-private partnerships that facilitate the implementation of circular economy initiatives.

Third, ports increasingly develop interconnected industrial cooperation networks in which energy, heat, water or materials are transferred between companies as resources rather than waste. This reduces losses and generates additional economic benefits.

Fourth, digital technologies and innovation play a crucial role by enabling the monitoring of material flows and the recovery of resources. Ports are developing digital platforms and new material processing methods, allowing them to implement circularity more effectively.

It is worth highlighting that many of the analysed projects do not concern only a single CE domain. Most greof them have a multidimensional character-simultaneously reducing CO_2 emissions, enabling the recovery of energy or heat, improving water management and reducing the amount of waste.

This indicates that circularity in ports is not a collection of isolated actions, but an integrated system of interrelated processes.

In conclusion, implementing the CE in seaports requires clear strategies, robust infrastructure, cross-sectoral cooperation and regulatory as well as technological support.

The findings of this analysis may assist other EU ports in preparing similar initiatives aligned with the objectives of the European Green Deal, the Fit for 55 package and the CEAP. The transformation of ports towards a circular model is achievable, but it requires a holistic approach and long-term investment.

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