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Circular developments of maritime industrial ports in Europe: a semi-systematic review of the current situation

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Abstract

Our current approaches to resource management are not sustainable. Businesses typically follow a linear approach where resources are not well utilized. Maritime ports are part of the problem, as they need to optimize the use of resources and generate negative externalities. However, they can also be important drivers of sustainability if they effectively transition to Circular Economy (CE). In this study, eight principles of CE and ten CBMs, are discussed and used to analyze ports in three areas of intervention. This paper analyzes current CE practices in European ports and the potential to adopt Circular Business Models (CBMs) to create value for port stakeholders and contribute to the United Nations Sustainable Development Goals (SDGs). Drivers and barriers to CE were analyzed, and the level of development was assessed. The ports studied are in Europe and are generally regarded as Maritime Industrial Ports (MIP). The methodology includes a Semi-Systematic Literature Review (SSLR) and a SWOT analysis to examine CE practices in maritime ports. This methodology helped enhance the analysis of Drivers and Barriers to CE transition. This study concludes that ports are developing circular practices and business models on the technical and biological flows, but the level of implementation is moderated to low. Six drivers for adopting CE principles were identified, including European ports' experience in circular activities and the Quality & Environmental Management System (EMS). In addition, seven barriers to CE were highlighted, including the diversity of port characteristics and the different interests and ambitions of port stakeholders that make it difficult to standardize measurements and transition to circularity. Circular development goals in ports should be integrated, and development must balance social, economic, and environmental sustainability. The findings and implications of this study will help Port Authorities (PA) in the strategy, policy development, and implementation of CBMs.

Keywords: Maritime industrial ports (MIP), Port sustainability, Circular economy (CE) and Circular ports, Circular business models (CBMs), Industrial symbiosis (IS)

Introduction

Our life systems work circular. There are no landfills; material flows, and one species' waste is another's food (EMF 2014). The sun provides energy, things grow and die, and nutrients return to the soil, and it works (Taylor 2020). If the living circular model works, can the way people think and work be changed to operate in a more circular and sustainable way? Using nature as an industry model, humans can use fewer resources and regenerate our planet (Raworth 2018), thus becoming more sustainable (Environment, Social and Economic). Waste is a human creation, and the more we have, the less we are sustainable.

The most commonly accepted definition of sustainability has its origin in the Brundtland Report of 1987 (Kuhlman & Farrington 2010), "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987a, 1987b). The concept has evolved to include three pillars: Social, Economic, and Environmental (Kuhlman & Farrington 2010) and environmental sustainability is the cornerstone. Today, people are compromising the existence of future generations due to the linear modus operandi of industries and societies.

Under the traditional Linear Economy (LE) approach, when virgin materials are turned into products for usage or consumption and then disposed of, excessive waste and pollution are generated (Rabaina et al. 2020), and (EMF 2019), and resource management is not optimal. LE is destroying our planet, aligning with capitalist ideas of "more is better" (Bonciu, 2021). For example, one can imagine a company that produces disposable plastic water bottles. The company extracts petroleum to make the plastic, uses energy to manufacture and transport the bottles, and sells them to consumers. After use, the bottles are typically discarded and end up in landfills or oceans as waste, which can take hundreds of years to decompose and harm animal species (United Nations, 2018).

The Circular Economy (CE) is today's essential alternative to Linear Economy (LE). It promotes sustainable practices by efficiently using resources, minimizing waste, and reducing environmental harm (EMF 2019; Velenturf & Purnell 2017). Industries, communities, and ecosystems can achieve long-term sustainability by adopting a CE approach. For instance, instead of disposing of plastic water bottles, CE allows for their collection, cleaning, and transformation into new bottles or other products through upcycling (McDonough and Braungart 2002). Alternatively, pyrolysis can convert plastic into fuel (Ghodke 2022). These are just a few examples of material flows within the CE model (refer to Fig. 2).

Maritime Ports play a vital role in global trade, transportation and economic development (UNCTAD 2020). As such, ports can be important drivers of change in many different ways, from facilitating global trade and connecting markets to promoting economic growth, driving innovation, and fostering sustainable development (Ghisellini et al. 2016). If large ports implement circular practices effectively, vast volumes of waste could be reduced, reused, recycled, upcycled, or cascaded. Large ports in Europe and elsewhere typically settle shipping, chemical & petrochemical, oil & gas, waste management, aluminum, steel, and other heavy industries. All these organizational practices generate much pollution due to their nature and processes (World Bank 2018).

This study investigates current CE practices of Maritime Industrial Ports (MIP) in Europe that contributes to a more resilient and sustainable ports. A MIP is a logistic and industrial node in global supply chains with a solid maritime character and a functional and spatial clustering of activities directly or indirectly linked to transportation, transformation, and information processes within global supply chains (Notteboom et al. 2022). Large industry clusters are located in these ports, such as chemical & petrochemical, steel, aluminum, manufacturing, and logistics (Sohar port 2023). There is a potential to develop symbiosis with a circular mindset(Monios & Woxenius 2020).

CE principles in port operations promote resource efficiency, waste reduction, and material reuse. This resource efficiency includes recycling, renewable energy use, and greenhouse gas emission reduction (Ghisellini et al. 2016). By embracing circular practices, ports can foster innovation through new technologies, business models, and partnerships (LOOP Ports 2018). Using circular practices can also create economic benefits such as cost savings, increased efficiency, and new business opportunities (Pieroni et al. 2018). Circular approaches also mitigate the environmental impact and minimize waste, pollution, and energy consumption, thereby protecting ecosystems, reducing carbon emissions, and enhancing sustainability (Greenport 2022). Additionally, adopting circular practices enhances port resilience to climate change, economic downturns, and supply chain disruptions, which aids in diversifying resources and improving adaptability (ESPO 2021). Ports are crucial in driving the transition to a CE by promoting circular practices across their operations and supply chains and harnessing innovation in areas like digitalization, automation, and smart ports (Philipp 2020), (Heikkila et al. 2022).

While numerous studies have investigated sustainability and circular economy (CE) in various industries, there is a lack of research specifically focusing on the application of CE in ports, particularly Maritime Industrial Ports (MIP) with industrial symbiosis. Compared to other industries, the Ellen MacArthur Foundation has conducted limited studies on ports, with one notable report titled "Completing the Picture: How the Circular Economy Tackles Climate Change" (EMF - Completing the Circle 2021). This report examines the role of CE principles in reducing greenhouse gas emissions within the maritime sector. The Ellen MacArthur Foundation is a renowned organization in the field of CE, actively promoting the adoption of CE principles across different industries, including the maritime sector (Tiana et al. 2020).

Research purpose

This study investigates current Circular Economy (CE) developments in several European Maritime Industrial Ports (MIP) while examining potential Circular Business Models (CBMs) to implement that will make ports more resilient by maintaining material flows in circulation and regenerating the ecosystem and contributing to achieving the SDGs. The specific research objectives are:

- To identify the current circular practices of several MIPs in Europe based on the CE principles.
- To analyze the circular practices of these ports based on the CE system model, including their stage and level of development
- To determine potential CBMs for implementation in line with current CE practices.
- To analyze Drivers and Barriers to circular developments affecting an effective transition to CE.

Different regions and industries worldwide, such as China, Japan, Scandinavian countries, the United States, and Europe, are actively promoting and making significant

Table 1 Ports in Europe analyzed

Ports in Europe	Country	Ports in Europe	Country
Rotterdam /Amsterdam Moerdijk	The Netherlands	Hamburg/Bremenhaven	Germany
Antwerp /Ghent/North sea port/ Bruges – Zeebrugge	Belgium	Gothenburg/Helsingborg/ Copenhagen -Malmo Aalborg	Sweden and Denmark
Marseille/Le Havre/Port of Boulogne sur-mer Dunkirk/Port of Nantes-Saint Nazaire	France	London/Southhampton/ Lowerstoft/Ramsgate/Dover Felixstowe	UK
Algeciras/Valencia Vigo/Barcelona/ Bilbao	Spain	Venecia/Genoa/Trieste Ravenna	Italy
Haminakotka	Finland	Thessaloniki	Greece
Koper	Slovenia		

Source: Own source

Most of these ports are MIP with circular initiatives. They are logistic and industrial nodes in global supply chains with a solid maritime character and a functional and spatial clustering of activities. They have different terminals depending on the cluster activities and stakeholders. Some of these terminals are Container, automobile, dry bulk (e.g. cement, iron ore…), liquid bulk (e.g. oil, gas, chemicals.). A conceptual framework of a MIP is illustrated in Fig. 3

progress in implementing circular economy (CE) practices (Patwa 2021; Ellen MacArthur Foundation, 2018). However, due to the vastness of these areas, this study focuses specifically on European ports. European ports are chosen for several reasons, including the establishment of a legal framework by the EU to support the transition to a circular economy. This framework includes the Waste Framework Directive, which sets recycling and landfill diversion targets (European Parliament, 2008). Furthermore, the European Commission's Green Deal, proposed in 2019, aiming to make the EU climate-neutral by 2050 and includes the Fit for 55 package and the CE Action Plan. The Fit for 55 package proposes legislative measures to reduce greenhouse gas emissions by 55% by 2030 compared to 1990 levels, while the CE Action Plan focuses on waste reduction and promoting sustainable production (European Commission, 2015).

The ports being investigated are medium to large-sized MIPs situated in Europe, primarily following a landlord-type governance model. When these ports oversee adjacent Industrial Zones (IZs), they have the potential to foster Industrial Symbiosis (IS). The selected ports are affiliated with reputable organizations such as ESPO, Green Port Initiative, or Loop Port projects, and they actively engage in circular or sustainable practices (ESPO 2023; Green Port Initiative 2023). A range of ports from various countries were considered, and their details are presented in Table 1.

To achieve these objectives, a Semi-Systematic Literature Review (SSLR) was conducted by collecting data on 115 articles published from 1987 to 2023. More details are explained in the research methodology.

The remainder of this study is organized as follows: The "Literature Review" section presents definitions and principles of CE introduces more details about MIPs and CBMs in general, and explains some applications of CE and CBMs in ports. "Methodology" outlines the scope of the study, explains how SSLR was conducted, and discusses the application of SWOT. "Research findings" link the results to the research objectives. "Conclusions and Discussions" summarizes the main points of the research, as it provides a detailed discussion of the results, implications, and limitations of this study. Direction for further research is also provided.

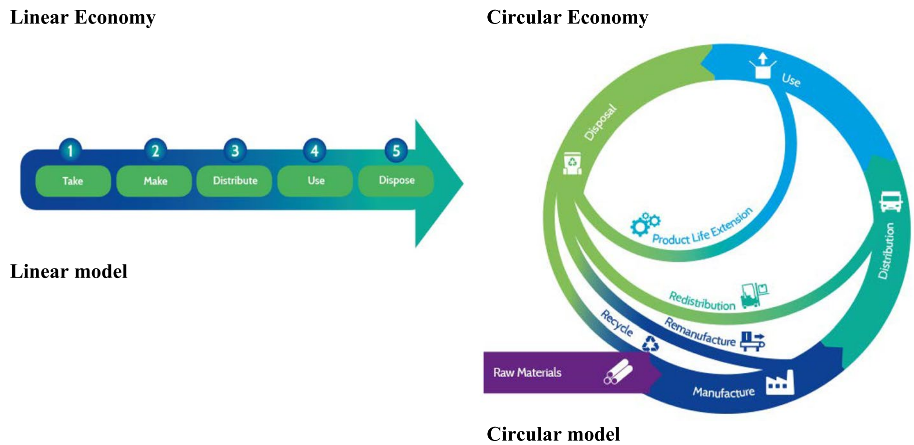

Fig. 1 Models of LE and CE. Source: Irisphere www.irisphere.be/en/circular-economy.html

Literature review

Introduction to circular economy (CE)

The CE promotes sustainability and resource efficiency by minimizing waste and maximizing the use of resources (Barros 2021). Unlike the Linear Economy (LE) with its "take-make-dispose" model, the CE aims to keep resources in use for as long as possible, reducing the reliance on finite resources (EMF on LE 2020). This involves sharing resources among industries and closing loops. See Fig. 1 for a comparison of the two models.

The Circular Economy (CE), according to the Ellen MacArthur Foundation (EMF), is based on three core principles: 1) Designing out waste and pollution, 2) Keeping products and materials in use, and 3) Regenerating natural systems (EMF 2019). However, other studies have identified additional principles to address the complexity of the topic (Geissdoerfer et al. 2016; Kirchherr et al., 2017). Table 2 presents eight CE principles that any industry aspiring to embrace CE practices should consider.

The CE approach requires a shift in the way we think about production and consumption and a redesign of business models, products, and services. This approach is for the port industry and any business, from car manufacturing to airplanes to retailing (EMF 2014).

CE has been implemented in ports since the 1990s in Industrial Zones (eco-industrial parks) such as the Kalundborg in Denmark, Stockholm Symbiosis in Sweden, and Kawasaki in Japan. These synergies allow the optimization of resources used and better cooperation in developing Industrial Symbiosis (IS) (Guillaume 2013). Developing IS waste of one company becomes the input of other closing loops. "The goods of today are the resources of tomorrow at yesterday's resource prices" (UNCTAD 2019). Different countries are developing IS in Europe, including Germany, Belgium, Denmark, France, Italy, Netherlands, Portugal, Spain, and the UK. (Massard, 2013). The potential for IS is still ongoing in existing cases, and there is still a wide range of opportunities for its application in businesses.

The concept of the Circular Economy (CE) traces back to industrialist Walter Stahel's idea of "closed loop" production systems in the 1970s (Stahel 2008). However, it was in the 1990s that the term gained broader recognition in Europe as a response to

Table 2 Principles of CE

Principles of Circular Economy	Purpose
Designing out waste and pollution	To eliminate waste and pollution starting from the by designing products and systems that are restorative and regenerative.
Keeping products and materials in use	To keep resources in use for as long as possible, through recycling, repairing, and repurposing
Regenerating natural systems	To restore and regenerate natural systems and using resources in a way that supports their long-term health and productivity
Shift to renewable energy sources	To move away from fossil fuels and transition to renewable energy sources like green hydrogen, solar, wind, and geothermal. This will help to regenerate the planet
Build resilience through diversity	To build a more resilient economy by diversifying supply chains and creating more local and regional systems
Applied cascades	To maximize the value of resources by using them in cascading systems, where the waste or by-products of one process become the inputs for another. This is the closing loop concept
Re-think and innovate	To rethink traditional business models and finding new and innovative ways to create value and meet consumer needs
Think integrated (in system)	To think about the entire system and how all the different parts are interconnected, in order to create a more sustainable and efficient economy

Source: By author adopted, with inputs form the Ellen MacArthur Foundation and others

concerns about resource scarcity, waste, and environmental degradation. The Ellen MacArthur Foundation, established in 2009, played a crucial role in promoting and popularizing the CE through research and advocacy efforts. This has led businesses and governments worldwide to adopt CE principles widely. Today, numerous countries, cities, and companies across various sectors are actively pursuing circular economy strategies and practices.

Since the early 2000s, the Circular Economy (CE) has gained momentum in response to concerns about resource depletion and environmental degradation. It aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Schroder & Raes 2021). In Europe, the CE is integral to the EU's Green Deal and the CE Action Plan 2020, aiming for a climate-neutral Europe by 2050 (European Commission 2020). The CE offers benefits such as reduced environmental impact and new business opportunities (Barros 2021). The Ellen MacArthur Foundation and its network of partners promote CE practices (EMF - Completing the Circle 2021). Transitioning to a CE requires collaboration, innovation, changes in consumer behavior, and supportive government policies.

Transitioning to a Circular Economy (CE) necessitates systemic and cultural changes, collaboration, and innovation across sectors (Ghisellini et al. 2016). It involves shifting mindsets and behaviors from the linear model to a sustainable and regenerative system. This requires redesigning products, adopting resource-efficient business models, and addressing policy and market barriers. Infrastructure investments are also essential, including recycling facilities, waste management systems, and transportation networks.

Despite the challenges, the CE offers compelling benefits such as reduced environmental impact, enhanced resource security, and new business opportunities. To ensure inclusivity and equity, access, affordability, and participation must be

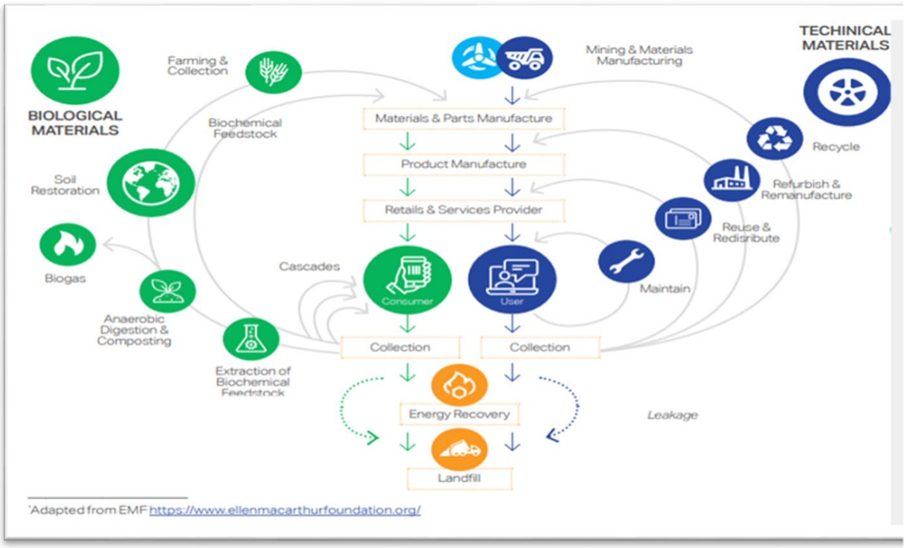

Fig. 2 CE system diagram (Butterfly) diagram representing the CE material flows. Source: The Ellen McArthur Foundation (EMF)

prioritized, involving diverse stakeholders in the CE transition. Embracing the CE is worthwhile and necessary for a sustainable future.

The Butterfly diagram, shown in Fig. 2 by the Ellen MacArthur Foundation (EMF 2019), is a widely recognized representation of the CE system. It offers a simple and intuitive visualization of the CE concept, serving as a valuable tool for policymakers, businesses, and stakeholders. The butterfly's body represents the convergence of the biological and technical cycles, fostering innovation and collaboration for developing new products and processes that integrate both cycles. This framework minimizes material leakage and reduces negative externalities (Korhonen et al. 2016).

According to a study published in the journal of sustainability in 2020, there were over 2.5 million peer-reviewed articles on sustainability between 2000 and 2019 (Giampietro et al. 2020). A search in the Scopus database for articles published between 2000 and 2021 using the term "circular economy" yielded over 6,000 peer-reviewed articles on the topic (Scopus 2021). However, when narrowed down to the context of ports, only 48 articles were found, suggesting limited information in this specific industry. While the Circular Economy is a relatively new concept, there is a growing body of literature exploring its potential benefits, challenges, and implementation strategies in various sectors.

Maritime industrial ports (MIP)

A MIP (Maritime Industrial Port) is a strategic hub for logistics, distribution, and industrial activities, offering excellent accessibility by sea, road, rail, and pipeline (Port of Rotterdam 2023). MIPs provide comprehensive facilities and expertise for loading, unloading, storage, transshipment, and processing of goods, catering to the specific needs of each company (Calvo 2018). They serve as nodes for industrial activities, such as manufacturing plants, refineries, chemical clusters, and warehouses, taking advantage of the port's location and transportation infrastructure (Calvo 2018). Additionally, MIPs play a role in renewable energy generation, waste management, and ship decommissioning (WSP, 2020). Ports can also support other economic sectors like tourism, fishing, and recreation (Port of Rotterdam 2023).

MIPs are predominantly governed by a landlord port model, where the Port Authority (PA) acts as a regulatory body and landlord, while private companies handle port operations (The World Bank, 2022). Examples of landlord ports include Rotterdam, Antwerp, New York, and Singapore. In this model, private companies lease infrastructure from the PA and are responsible for maintaining their own equipment and employing dock labor. Some ports have expanded their role as developers and operators of adjacent Industrial Zones or Free Zones (Langen, Henrik, & Hallworth, 2020). Successful Business Models (BMs) are crucial for MIPs to thrive in a dynamic market (The World Bank, 2022).

Circular business models (CBMs)

A business model (BM) is a plan or strategy that outlines how a company creates, delivers, and captures value in the marketplace (Baden-Fuller 2010). It is essential for any business to have a well-defined and effective business model in order to be successful. These models can be based on the principles of the CE, which seeks to create a closed-loop system in which resources are used and reused in a continuous cycle, and these are conceptualize as Circular Business Models (CBMs).

Reducing a company's environmental footprint, trimming operational waste, and using expensive resources more efficiently is a necessity, and certainly appealing to top management. However, creating a CBM is challenging, and taking the wrong approa can be expensive (Harvard Business Review 2021). Success depends on many factors, but perhaps the most important is choosing a strategy that aligns with the company's capabilities and resources and addresses the constraints on its operations. Different general CBMs were identified in the literature and are summarized in Table 3 below.

Not all CBM are new. The concepts of recycling, reuse, and repair have existed for some time now (Awan & Sroufe 2022). The sharing of under-utilized household possessions also has a long history, and the provision of access to products, rather than ownership of them, is not so different from traditional product leasing. What is new is the growing diversity and sophistication of some CBMs, the way people are re-thinking business operations, as well as the range of sectors that adopt them (OECD 2019). The overall goal of these new CBMs is to lessen an organization's dependence on new resources.

Research methods

This study aims to explore the current CE developments in main European MIPs and potential CBMs to implement. A SSLR was conducted to collect data from a range of sources, including academic databases, grey literature, and online sites, using a predetermined search strategy. Following the literature review, a thematic analysis was conducted to identify key themes and patterns in the data. By looking into diverse data sources, this study offers valuable insights into the experiences of different European ports in the planning and implementation of circular projects and provides a basis for future research and circular practices implementation.

Table 3 Technical and Biological Circular Business Models (CBM)s

Model	Elements
Delivery on demand (DOD)	Producing a product or providing a service only when a consumer demand has been quantified and confirmed
Sharing models and collaborative consumption (SCC)	Industrial ports allow and promotes facilitating sharing of under-utilized products or equipment, and can therefore reduce demand for new products or equipment, and their embedded raw materials. It also enhance utilization and capacity management. (Sharing)
Design for recycling or dematerialization (DFR)	Industrial ports demand from suppliers to modify designs to be more modular and reengineer to allow more recycling or dematerialization (maintain/prolong)
Retain Product Ownership (RPO) or Product as a Service (PSS)	Industrial port suppliers and contractors offer products for use with retention of products ownership which incentivizes increase in resource productivity along the whole life cycle (reduce/redistribute)
Product Life Extension (PLE)	Industrial ports extend the use period of existing products, slow the flow of constituent materials through the economy, and reduce the rate of resource extraction and waste generation (refurbish/remanufacture)
Resource Recovery, Recycle and Upcycle (RRU)	Industrial ports host facilities that recover usable resources or energy from waste or by-products. Ports offer logistics capabilities as an added-value service. (recycle)
Green Supply Service (GSS)	Port suppliers replace traditional material inputs derived from virgin resources with bio-based, renewable, or recovered materials, reduce demand for virgin resource extraction in the long run (parts and product manufacturing/service provider/purchasing)
Sustainable Food, Agriculture and Aquaculture (SFA)	Organizations in the port can multiply the value of this sector with product diversification, product differentiation, high-value and premium-quality products and services, waste reduction, resource and land use efficiency improvement. Reduction of food waste should be a priority. (cascading & farming and collection)
Cascading for Medical and Wellness (CMW) (by product)	The principle of cascading, the sequential and consecutive use of resources, is a potential method to create added value in circular economy (CE) practices. Cascading can be applied for other sectors such as food by-product or wood, textiles, coffee grounds and tyres (cascading)
Bioenergy, Biomass and Biochemical Production (BBB)	Industrial ports explore production of energy with non-fossil fuels. This vision will require intensive research in energy storage systems. As for the materials and biochemical sector, cutting-edge technologies need to be developed and employed to convert biomass and agricultural by-products to high-value commodities such as bioplastics, fibers and pharmaceuticals. (Bio-feedstock, anaerobic digestion, regeneration)

Source: By author, with inputs form OECD, Harvard Business review, Bio-circular economy model, and other authors

Scope of the study

This study involves mainly MIPs, represented in Fig. 2, where the Port Authority (PA) is a public entity that manages, operates and develops the port and industrial area. The PA makes sure there is infrastructure for public or private organizations to develop superstructure and operate. They acts as enabler and facilitator of sustainable growth, and it is a regulator (Port of Rotterdam, 2022), (Port of Antwerp, 2020).

These ports contribute largely to the economy and social development of the country and have the potential to generate closed loop economy models with major impact

Table 4 Examples of Industrial symbiosis

Industrial areas—Eco-Park	Description
Kalundborg Symbiosis	The symbiosis involves a network of companies that share resources and by-products in order to reduce waste and improve resource efficiency
Kwinana Industrial Area	The area is home to several companies that collaborate to reduce waste and promote sustainability, including a cement company that uses waste from a nearby nickel refinery as a raw material
Port of Rotterdam	The has implemented several industrial symbiosis initiatives, including the Rotterdam Heat Grid, which uses waste heat from local industries to heat homes and buildings
Symbiosis Center Denmark	The organization connects companies across Denmark and helps them find opportunities for collaboration and resource sharing
Port of Amsterdam	The port connects companies and organizations in the port area to exchange resources such as energy, water, and waste. For example, residual heat from waste-to-energy plants is used to heat greenhouses, and steam from industrial processes is used to generate electricity
Kemi-Tornio Industrial Park	In this port the waste heat from a stainless steel plant is used to dry wood chips, which are then used as fuel in a bioenergy plant
Symbiosis in Güssing, Austria	The town has a biogas plant, which produces electricity and heat from agricultural waste and organic materials. The heat generated by the biogas plant is used to heat buildings and greenhouses, and excess electricity is sold to the national grid
Høje-Taastrup, Denmark	The municipality of Høje-Taastrup in Denmark has implemented an industrial symbiosis program, which connects companies to exchange resources such as energy, water, and waste. Example, Waste heat from a brewery is used to heat a swimming pool, and excess water from a pharmaceutical plant is used for irrigation

Source: By author based on literature reviewed

when implementing Industrial Symbiosis (IS). Industrial port effectively can balance public interest of the society and private interests of shareholders and can be an important driver of circularity. IS refers to the collaboration and resource sharing between companies in order to create a closed-loop system and reduce waste (Neves, Godina, Azevedo, & Matias, 2019). Around the world, there are a number of well-known instances of IS. Some examples are presented in the below Table 4.

These are a few examples of IS in Europe, and there are similar initiatives taking place across the continent. Overall, the trend towards industrial symbiosis is expected to continue as more companies and governments recognize the environmental and economic benefits of adopting CE practices. The following Fig. 3 illustrates the Maritime Industrial Port (MIP) system where they collaborate or manage the Industrial parks (Eco-parks).

In a landlord port model, the port infrastructure is typically owned by the port authority or the government entity responsible for managing the port. These ports often have waste reception facilities and industrial zones adjacent to the port, which are managed by the port authority. The presence of these facilities attracts a diverse range of large ships, tailored to the needs of the companies operating within the port or industrial zones. This model promotes economic growth, environmental protection, and efficient maritime operations.

A semi-systematic literature review (SSLR)

A Semi-Systematic Literature Review (SSLR) wasconducted to analyze the CE models approach and its current application in MIPs. This method was selected because the topic of CE is conceptualized differently and studied by various groups of researchers

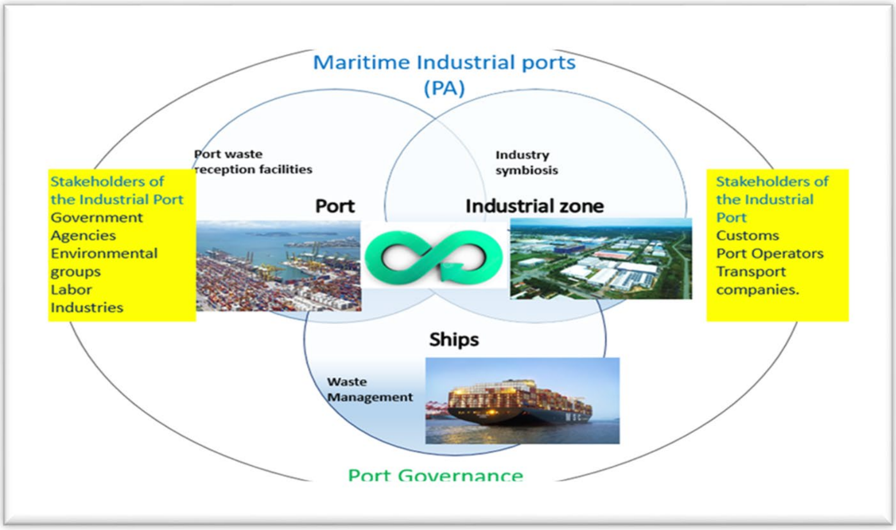

Fig. 3 A conceptual framework of Maritime Industrial Port (MIP). Source: Elaborated by the author

with diverse disciplines, and may hinder a full systematic review process (Wong 2013). While a systematic review follows a predefined and reproducible search strategy to identify and select relevant studies, a semi-systematic review may have a more flexible search strategy and may include a wider range of literature sources (Snyder, Literature review as a research method, 2019). Application of CE was investigated in different sectors beside the ports as well.

This SSLR approach included search methods, inclusion and exclusion criteria, data extraction, and synthesis following the guidelines of (Petticrew and Roberts 2006) to have accurate, precise and trustworthy background information. An effective SSLR research method creates a firm foundation for advancing knowledge and facilitating theory development (Webster and Watson 2002). By integrating findings and perspectives from many empirical findings, a literature review can address research questions with a power that no single study has (Snyder 2019).

In this study, the researchers reviewed studies published after 1987 when the Brundtland Commission developed guiding principles for sustainable development, as it is generally understood today. This was an important milestone in port and shipping sustainability and part of the literature reviewed in this report. The research terms were a combination of: “Sustainability and port sustainability”, “Circular Economy or Circular Economy in ports” OR “circular transition in ports”, “Circular Business Models (CBM)”, and “Industrial Symbiosis (IS)”. Search for titles and keywords was done in broad databases such as ISI, Science Direct, directory of open access journal, Web of Science, Elsevier Science, IEEE Explore, complementary index, Library Database and EBSCO.

The research was limited to studies in English or Spanish language. The review includes academic peer-reviewed paper, grey literature such as conference proceedings, latest news, book chapters, and technical reports from port stakeholders, in addition to selected international and regional reports, projects, and studies. The grey literature was included to ensure diversity of views particularly due to lack of coverage of some

Table 5 Inclusion and exclusion criteria

Criterion one		Criterion two	
Inclusion of resources	Academic peer reviewed article that are relevant to the themes and contributed to fulfill the objectives of the research Grey literature based on the relevant of information discussed and the extra useful knowledge on the topic. Reports and news of the European Commission, ESPO, wbcsd, the Ellen MacArthur foundation, World Port Sustainable Program (WPSP), Organization for Economic Cooperation and Development (OECD), International Association of Port and Harbors (IAPH), Green port Initiative, and Loop Port were key inclusions. In addition to reports of consulting companies such as Accenture and Mc Kinsey	Exclusion of resources	Academic peer reviewed articles that did not thoroughly discuss the review topic such as CE in ports or industrial symbiosis Grey literature studies with small differences that included repetitive results, had weak context or references, particularly conference proceedings, in addition to proceedings and reports, which were discussed thoroughly in academic literature

Source: Elaborated by the author

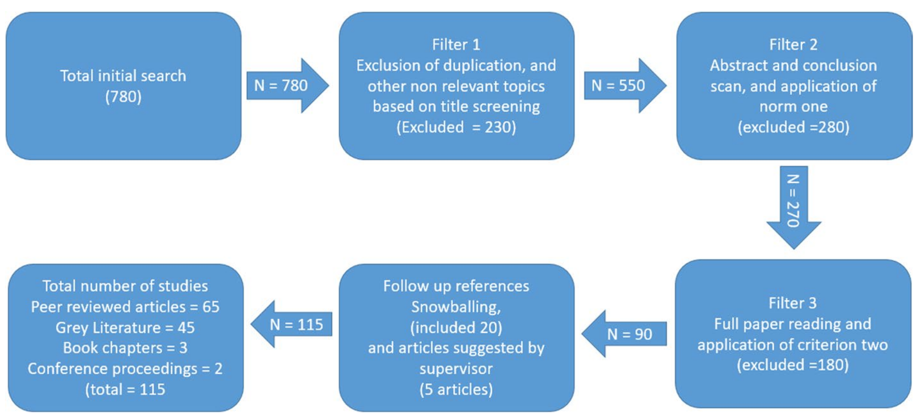

Fig. 4 Filtering Process on systematic and Semi-Systematic Literature Review. Source: by the author

concepts in academic literature. The total number of studies initially identified from different disciplines and ports were 780. However, relevance in information is pursued rather than quantity of literature. Limiting the scope to what is necessary was ensured by establishing the following inclusion and exclusion criteria which is futher explained in Table 5.

1. *Criterion one*: Provided a guideline on the type of peer reviewed and grey literature included in the synthesis, details presented in Fig. 4.
2. *Criterion two*: Is judgmental, it restricts the number of studies included to select the most relevant to the research topic. Therefore, a test–retest process was performed, i.e. researchers conduct a second extraction process from a random selection of pri-

mary studies to check data extraction consistency, thus, the result was consistent (Kitchenham and Charters, 2007).

The inclusion and exclusion criteria are demonstrated through the filtering process shown in Fig. 4. Following-up references using a snowballing approach added 18 articles. The final total number of studies included is 83. The majority of studies found are in the topic of sustainability. In addition, in CE more than 300 peer reviewed articles were identified but a search for CE in ports revealed less than 100 publications, showing limited research on the topic.

After the review of 115 studies, qualitative data of European ports, good CE practices, barriers and drivers, and levels of development are collected. IS on different ports are documented due to their importance in CE exponential development and sustainability. Together with the SSLR, a SWOT analysis is elaborated to help design effective strategies for ports transitioning to a CE.

SWOT analysis

A SWOT analysis tool is elaborated to document internal strengths (S) and weaknesses (W) of European MIP CE implementation, as well as external opportunities (O) and threats (T). The analysis is used to find drivers and barriers to circular practices in MIP. PA could use the information to set goals on circularity and strengthen competitive advantage of industrial ports aiming to benefit in the long term from their sustainable and circular commitments. Table 10 shows the SWOT analysis applied in ports.

Research outcomes

The foundation for CE is based on eight principles, and the application in ports is explained in point 4.1. Tables 6, 7, and 8 identify current CE practices of main MIPs in Europe based on these CE principles. Circular practices need to be implemented more in MIPs by applying different CBMs. Circular practices will help ports reduce gas emissions and substantially support planet Earth's regeneration. Ports already accommodate industries that are actively involved in waste treatment, collection, and shipment. Many of these wastes are highly polluting materials, mainly metals, plastic, construction, and biomass (Loop Port 2018). This makes ports ideal locations to implement circular practices to reduce worldwide emissions of GHG and other types of waste and increase energy efficiency with a high impact on a region and country (Biwei et al. 2012). The following are CE practices of the main MIP in Europe based on the CE principles.

Application of CE principles in MIP

Over 80 percent of all product-related environmental impacts are determined during the design phase (European Commission 2020). MIPs need to work with eco-design of equipment, packaging, building infrastructure, and superstructures to reduce the environmental impact of materials, including energy consumption, through their complete life cycle. → **Designing our waste and pollution in ports.**

MIP need to provide and keep improving port waste reception facilities and promote IS in their facilities to optimize the resources used. Ports need to reduce the time for handling abandoned cargo so items can be in circulation faster. It is more relevant for

Table 6 Circular assets and equipment

Port Initiative/projects	Ports (Examples)	Contribution to CE flows		Development Stage	Potential CBMs
		Technical	Biological		
Provision of fossil-free fuels to power boats, vehicles, tug boats, machines, etc	Gothenburg/ Birmingham/Bilbao/Marseille/ Antwerp/ Amsterdam/ Rotterdam		**X**	Preliminary studies for modern biofuel (Biofuel and green hydrogen). Operational (Electric power and HVO)	BBB/ GSS/ SCC/ DFR/RRU
Provision of OPS to decarbonize shipping	More than half of European main ports have OPS		X (If clean energy is used)	Operational and under expansion. Only a few ports have the capacity to provide OPS to large cruise and ferries	BBB (if energy source is fossil free) GSS/DFR/SCC
Clean water treatment facilities to protect the sea and meeting regulatory requirements	Rotterdam/Marseille/Amsterdam/Antwerp/ Valencia/Marseille/		X	Operational	SFA/ CMW/GSS
Installing solar systems for energy production (on shore and offshore)	North sea port/Denmark/ Rotterdam	X	X	Operational and expanding. *Panels are recyclable improving the circular flow*	SCC/ DFR/ PLE/ RRU/ GSS
Recovering waste heat from waste incineration facility and connect it for district heating	Antwerp/ Marseille		X	Operational and expanding	GSS/ RRU/ DFR/ SCC
Planting trees, and protecting wildlife and promoting biodiversity	Denmark/Cava/Rotterdam/ Gothenburg/ Dover		X	Operational** Contributing to the natural circular cycle. → Regenerative	SFA/CMW
Providing a site suitable for off shore energy operations using clean energy Production of off shore wind facilities	Lowerstoft Rotterdam/Amsterdam/Antwerp/north/le Havre /Barcelona/Bilbao		X X	Operational and inexpantion	BBB/GSS/DFR/SCC
Implementing hybrid shipping	Hamburg Oostende		X	Operational and in expansion	GSS/BBB/RRU/DFR
Replacing of 60% of a mobile fleet with electric and hybrid vehicles	Algeciras		X	Operational and in expansion	GSS/BBB/RRU/DFR
Digitalization and 3D operating for operations and maintenance	Haminakotka	X		Operational and in expansion	RRU/PLE/SCC
Enlarging cranes to enable their use for bigger vessels	Valencia	X		Operational and in expansion	PLE/RRU
Installation of new buoys stabilized against UV rays, maintaining color and a longer service life	Ramsgate	X		Operational and in expansion in different ports	RRU/PLE
Installation of SMART grid to manage electrical efficiency	Vigo		X	Operational and in expansion in many ports	SCC/DFR/ RRU/BBB

Table 6 (continued)

Port Initiative/projects	Ports (Examples)	Contribution to CE flows		Development Stage	Potential CBMs
		Technical	Biological		
Charging batteries with energy produce by wind	Amsterdam		X	Operational	BBB/GSS/ RRU/ SCC
Applying a method to grind beacons and repaint it, allowing it to be reused	Copenhagen Malmo Port	X		Operational	DFR/PLE/RRU
Stimulating cycling to employees by getting company bikes and providing benefits	North sea port	X		Operational	SCC/RPO/GSS
Implemented a policy to stimulate car-pooling if not alternative to use other more clear transportation	North sea port	X		Operational	GSS/SCC

Source: By the author

Table 7 Circular flows within ports

Port Initiative / project	Ports (examples)	Contribution to CE		Development Stage	Potential CBMs
		Technical	Biological		
Using sand from dredging to make cement or other uses	Aalborg/ Dunkirk/ Marseille	X	X	Operational and used in some ports	SCC/RRU/GSS/CMW
Converting sea sediments into bricks for construction	Koper	X	X	Operational	RRU/GSS
Recovery of marine waste to reconvert them into clothes	Valencia	X		Operational	RRU/GSS/CWM/PLE
Recycling 100% of a shipping company plastic containers	Valencia	X		Operational	RRU/GSS/PLE
Reuse of old stables in the port (refurbishment)	Thessaloniki	X		Planned	RRU
Repurposing fish by-products as raw materials for nutraceutical, functional goods, cosmetics and animal nutrition	Boulogne-Sur-Mer		X	Operational	CMW/SFA/GSS
Limiting lost nets, recycling and developing biodegradable nets for sustainable production of seafood	Italy	X	X	Operational	CMW/SFA/GSS/RRU/PLE/DFR
Carbon Capture Utilization (CCU) and Carbon Capture Utilization and Storage (CCUS)	Belgium/UK/Holland/Sweden		X	Use in small scale and in studies in different ports	RRU/GSS/DFR/SCC
A shipping company takes the initiative to recycle 100% of its plastic containers	Valencia	X		Operational	PLE/RRU
Developing a comprehensive management system for waste from fishing ports (including food, plastics, polystyrene boxes, disused gear and marine litter)	Spain	X	X (cascade)	Operational and in expansion	CMW/SFA/GSS
Investing in energy infrastructure for residual heat (e.g. providing heating through sea power)	Rotterdam/ Tallinn		X	Operational and in expansion depending of the port strategy	BBB/SCC/DFR
Utilizing rainwater from warehouses roofs and stores it. Tap water could be used if there is a lack of rainwater and monitors the overall use	Spain		X	Operational	SCC/DFR/RRU/GSS/SFA

Table 7 (continued)

Port Initiative / project	Ports (examples)	Contribution to CE		Development Stage	Potential CBMs
		Technical	Biological		
Doing safety environmental awareness for cruise waste management	England			Operational No circular, but with potential contribution to a circularity	RRU/PLE
Recovering energy from cruise ships' wastewater by recycling and re using 100% of the wastewater for any non-potable use, such as cleaning water or irrigation	France		X	Operational and in expantion	SCC/DFR/RRU/GSS/SFA/BBB
Provide new use to shipping containers as housing, urban furniture or decoration Re-use of recycled containers for the construction of a terminal	Valencia Sevilla	X		Operational and with potential for expansion	SCC/DFR/RPO/PLE/RRU/GSS
Reusing flows of retained goods, which generally end up being abandoned or destroyed	Valencia	X		Operational	RRU/PLE

Source: By the author

materials and resources with short lifespans, such as food which can cause vast amounts of waste without appropriate regulations and resource recovery processes. → **Keeping products and materials in use.**

MIP can build resilience through diversity due to the availability of resources and ecosystems that can be regenerated by the actions of ports (water, forests, wildlife, and birds). Ports must contribute to developing the ecosystem around them. Denmark or Rotterdam, for example, and planting trees and protecting wildlife. **Regenerating natural systems.**

Renewable energy is a crucial aspect of producing circular products and resources; ports have to consider how the components of renewable plants are designed, manufactured, built, and managed. CE has to be baked into the energy transition by design to ensure the world has a sustainable supply of raw materials. Green design will take concerted action from companies and regulators. The shift to green hydrogen and carbon capture for energy purposes should be an essential strategy for different ports, and alliances must be made to benefit other ports and communities. Green hydrogen and carbon capture will considerably reduce CO2 emissions. → **Shift to renewable energy sources.**

An economy can get more excellent value from diversity by sharing strengths and having a large pool of resources to draw on; such a system can also bounce back from the shock of events. By implementing circular practices, a port is resilient, continuing to

Table 8 Port and circular market

Port Initiative/ Project	Ports (examples)	Contribution to CE: Technical	Contribution to CE: Biological	Development Stage	Potential CBMs
Developing IS in Industrial Zones	Denmark Finland Sweden Netherlands	X	X	Operational and in expansion in many different locations	All 10 CBMs
Setting ships' repair, and new building by using modular design and standardization of vessel parts for better refurbishing, repair, and upgrade	Greece Portugal Poland Spain	X		Operational (repair)	SCC/DFR/PLE/RRU/GSS
Ship decommissioning and recycling	Denmark UK Cyprus Aberdeen	X		Operational	SCC/DFR/ PLE/RRU/GSS
Converting non-recyclable plastic into Diesel by pyrolysis (Integrated Green energy Solution)	Amsterdam	X		Operational	BBB/GSS/ RRU/PLE/DFR
Hire of mechanical means and loading/unloading tools	Thessaloniki	X		Operational	SCC/RPO/PLE/RRU/GSS (if uses Non-fossil fuel power
Container repair	Limassol	X		Operational	PLE/RRU
Setting up a corridor to transport blue ammonia from Norway to Rotterdam. The blue ammonia will be produced in Norway from Natural gas with CCUS	Holland		X	In development	SCC/PLE/RRU/GSS/SFA/CMW/BBB
Building a dedicated quay to repurpose decommissioned ships and rigs	Denmark	X		Operational	SCC/DFR/PLE/RRU/GSS
Carloop project enabling to extend the life of car parts and raw materials by providing logistical and linking buss	Belgium	X		Operational	PLE/SCC/DFR/RRU/GSS
Develop a new green infrastructure supporting the production of offshore energy of wind farms	UK		X	Operational and in expansion	RRU/BBB/GSS/PLE/PSS/SCC
Becoming a hot-spot for the CE in Europe connecting businesses	Holland	X	X	Operational and in expansion	10 CBMs

Table 8 (continued)

Port Initiative/ Project	Ports (examples)	Contribution to CE		Development Stage	Potential CBMs
		Technical	Biological		
Ensuring sustainable production of mussels in farms while avoiding plastics contamination	Italy	X		Operational	SFA/CMW/RRU/PLE/SCC
Converting Non-Recyclable waste into advance biofuel (Methanol)	Amsterdam/Rotterdam		X	Operational	BBB/GSS/ DFR/SCC
Upcycle Factory (linking lower value industrial waste streams to value creation chains)	Amsterdam	X		In development (pilot)	RRU/GSS/PLE/SCC/PLE

Source: By the author

carry out its mission in the face of adversity because it closes loops with materials. If we maintain products and materials in circulation, redesign products to be more easily upgraded, and design out waste, we contribute to resilient production. Being circular will also translate into a resilient SC discussed extensively during the Covid19 pandemic. → **Build resilience through diversity.**

Cascading maximizes resource effectiveness by using biomass in products that create economic value over multiple lifetimes. This approach to production and consumption states that energy recovery should be the last option only after all higher-value products and services have been exhausted. This concept is often associated with the forestry sector, food, and wealth. Industries in IZ with such clusters need to promote cascades. This is linked to building resilience and keeping products and materials in use. → **Applied cascades.**

To innovate is a worldwide general principle that aims to enhance productivity and be sustainable. In the last years, all the renewable energies and CCUS developed in port facilities have been due to innovative ideas. Now is the time to use more technology in waste management. → **Re-think and innovate.**

A CE is not about one firm or port changing one product or service; it is about many actors working together to create adequate flows of materials and information, with everything increasingly powered by renewable energy. When we think about systems, we see the connection between people, places, and ideas. By applying system thinking in ports and eco-parks, we begin to see how we can create opportunities to generate economic, environmental, and societal gains, and we create a balance. → **Think integrated (System Thinking).**

CE implemented in industrial ports significantly impacts sustainability due to their large size of operations, influence in Industrial Zones (IZ), energy use, logistics activities, and variety of stakeholders interacting. Already different circular activities are undergoing in industrial ports around Europe, such as green hydrogen or biofuel production or upcycling of materials generating CBMs such as Design for Recycling (DFR) or Resource

Recovery, Recycle and Upcycle (RRU). However, there is more to be done to make a change in the regeneration of planet Earth.

CE implementation and alignment with the CE system model

Three main areas of port intervention are identified to encourage CE implementation and developing CBMs (Loop Port 2018). These areas are:

1. *Circular assets and equipment of industrial ports* Through maintenance and smarter use, ports can optimize the capacity and lifetime of existing port equipment and infrastructure and facilitate the transition to a CE. These assets and equipment include cranes, conveyor systems, container handling equipment, tugs and pilot boats, mooring equipment, berthing equipment, buoys, grid, OPS, and more.
2. *Circular flows within industrial ports* Waste generated by port activities is another area where ports can facilitate the transition to CE. These will allow better use of internal resources of the port, Industrial zones, and transport network converging in the port. Industrial Symbiosis fits in this area of intervention.
3. *Industrial ports and circular markets* Ports can also enable other industries to be more circular by developing new activities connecting supply and demand for resources and materials moving through the port. These will support the development of a circular approach to Supply Chains and transport networks. Industrial Symbiosis is applied in this intervention area when ports manage industrial parks.

Tables 6, 7, and 8 show different CE practices in European ports, the type of material flow, and CBMs, in these three different areas of intervention. CE practices include initiatives (proposed projects and feasibility studies), projects, or ongoing operations.

Circular assets and equipment of industrial ports

Table 6 shows that renewable and sustainable energy investments are predominant in some large ports. Regulations to stimulate the transition to more circular activities are essential. It also shows that ports are starting to use more innovative technology, but CE in maintenance needs to be better documented in CE or sustainable article topics. OPS terminal operators and shipping companies are joining forces to increase clean and cost-efficient energy access.

Circular flows within ports

Table 7 shows that Ports are crossroads of different kinds of waste generated due to their operations or by stakeholders. More examples need to be documented as good practices.

Ports and circular markets

Table 8 highlights the potential of ports as key drivers of circular and sustainable projects by connecting stakeholders and providing incentives. Notable examples include the financial benefits derived from sustainable practices promoted by Germany, Sweden and other Scandinavian countries and the extension of the lifespan of car parts through effective collaboration between ports and other stakeholders. An illustrative case is the port of Aberdeen in Scotland, which aims to establish itself as a decommissioning hub, generating employment opportunities while promoting circular economy principles. The port intends to maximize material reuse, repurposing, and recycling during the decommissioning process (Greenport 2022).

SWOT analysis

The following are Strengths, Weaknesses, Opportunities, and Threats affecting a better transition to a CE, summarized in the following SWOT in Table 9. These are essential inputs for Drivers and Barriers to CE implementation.

Drivers and barriers to circular implementation

To identify the main Drivers and Barriers to CE, more than 115 articles were reviewed, and the SWOT analyzed. This Drivers and Barriers can help managers of other ports identify opportunities for improvement, develop strategies to address the barriers and leverage the drivers to achieve the desired outcomes.

Drivers

- *Setting a CE zction plan embedded in the port environmental plan*: Port Authorities should create cultural changes and governance to promote the circular mindset. They must set a circular vision and embed it in the environmental plan. From a commercial point of view, if ports want to become more attractive to customers, they need to protect the environment and inform their customers. EMS standards such as the ISO 14001, ISO 14044:2006 (Life Cycle Analysis implementation), and Eco-Management and Audit Scheme (EMAS) will help ports identify achievements and environmental improvement. Implementation of the ECOPORT tools "Port Environmental Review System (PERS)" and "Self Diagnosis Method (SDM)" is particularly effective in the pathway to an ISO or EMAS standard.
- *Deciding on CBM(s) to implement for business sustainability*: Ports must set CBMS to be implemented. Innovative models allow ports to take advantage of changing customer demands and expectations. If ports cannot innovate and shift their business models to be more circular and sustainable, they could be displaced by other ports that are better able to meet customer needs. Innovative CBMs on value chains for products such as plastic, textiles, rubber, metals, cement, chemicals, or biomaterials will reduce high CO2 emission because these are high pollution emitting materials.
- *Applying disruptive technology*: New technological innovations have a great capacity to enable CBMs: 1) Digital (IoT, big data, blockchain, and RFID) helps ports to track resources and monitor utilization and waste capacity. 2) Physical (3D printing, robotics, energy storage and harvesting, modular design technology, and nanotechnology) helps Port Authorities and companies in the port to reduce production and material costs and reduce environmental impact. 3) Biological (bio-energy, bio-based materials, biocatalysis, hydroponics, and aeroponics) help ports and companies in the port aiming to become energy hubs move away from fossil-based energy sources (Wbcsd 2015). Digitalization could assist in closing the material loops by providing accurate information on the availability, location, and condition of products.

Table 9 SWOT Analysis for European Maritime Industrial Ports

Strengths	Weaknesses
European ports' commitment to environmental protection and sustainable development evidenced by the Environmental Management Plan (EMP), which highlight the potential CBMs to apply Experience of European ports in CE development and a few CBMs implementation Port efforts to fulfill the requirements for being environmentally certified (ISO 14001, PERS, and EMAS) and to publish their environmental and sustainable reports Existence of environmental policy in place (96% of ports) Port waste and energy circular activities interests Rise in providing of OPS and LNG bunkering, and interests in Green hydrogen and CCUS. In 2020 one third of ports made LNG bunkering available Port Reception Facilities Directive for ships engaged in sustainable waste management onboard Provision of rewards for vessels that hold an environmental certification Implementation of 4IR technologies	Linear approach as an embedded protocol in ports and industries The relatively short life cycle of energy projects due to constant innovation creates uncertainty for energy projects Reduction the environmental training program for port employees The small decrease in the provision of differentiated Fees for "green" vessels as per the tax incentives (around 57% of ports provide environmentally differentiated fees) Port diversity with challenges for standardization of measurements and practices Investment costs due to the inclusion of environmental measures in charging schemes Non-harmonized regulations at port areas Lacking suppliers and partners offering sustainable solutions and enhanced cooperation Lack of work with and alongside the EMF

Opportunities	Threats
Availability of Environmental Management Indicators (EMI) set by the ESPO Port network organizations such as EcoPort, ESPO, IAPH, and Loop Port Partnerships and constant dialogue between port stakeholders Innovative business models rise with circularity UNSDGs and targets, Paris Agreement, IMO target, and the European Green Deal, with the fit for 55 package European Commission circular action plan adopted in 2020 MARPOL Annexes I,II, IV, and V ratified by European nations Availability of disruptive technologies (Digital, Physical and Biological) that help port implementation in CE Development of entire value chains for plastic, textiles, rubber, biomass, and chemicals for new CBMs System thinking approach (integration) to tackle sustainability and circular economy The availability of Circulytics and Circular transition Indicators (CTI) to support the organization's transition toward the CE	Lack of societal pressure GDP as a measure of the productivity and economic development of countries Lack of harmonized legislation High costs of circular development initiatives in renewable energy, financial mechanisms and uncertainty in the technology life cycle High-energy consumption of green hydrogen Different CBMs not sufficiently assessed The diversity of the European port and maritime sector translates into difficulty of replicating best practices in other ports Funding and financing constraints for these initiatives, there is no time and no money to waste Inadequate stimulation of Education, awareness, and training of the workforce No universally accepted system to determine the environmental impacts in port Lack of Integration (system thinking) Lack of standardized policies for clean energy The Policy framework is insufficient for emissions reduction target of a net 55% of the fit for 55 pack

Source: Elaborated by the author

- *Providing incentive mechanisms by governments and port authorities*: Rewards for the good sustainable practice of ports and CO2 emission reduction motivate shipping companies and other stakeholders to move to a more circular and sustainable way of doing business. Rewards are an essential mechanism to achieve environmental priorities such as shipping decarbonisation, shipping certifications, air quality improvements, climate change mitigation, energy efficiency, and pollution reduction. Industrial ports have access to waste, which could be used efficiently, such as creating biofuel, fertilizers, and others. Suppose industrial ports are developing industrial zones (eco-parks). In that case, a multi-pronged approach must help small and growing businesses be circular and reach net zero emissions.

- *Enhancing partnership and collaboration*: Collaborative efforts such as Private–Public-Partnership (PPPs), joint efforts among several government ministries, or ports of the network enhance the experience needed to create effective circular models and policies. To enhance competitive advantage, European ports must cooperate with port networks and stakeholders for digitalization, keep up to date with EMS, provide rewards to stakeholders protecting the environment, and convert waste into materials. It is important for an alliance of governments supported by stakeholders willing to work together, share knowledge, and advocate for the global CE transition to more sustainable management of natural resources at the political level and in multilateral fora (Migliorini, 2022). Aiming for this better government integration, the global alliance on CE and resource efficiency (GACERE) kicked off in 2021.
- *Implementing measuring tools that support the transition to a CE*: Industrial ports should quantify the CE and environmental impacts of their activities to be more sustainable. Ports should have a sustainable port index considering CE implementation; this should be publicly available and agreed upon at the world level. A port index help prioritize investments (especially regarding public funds),, evaluate the success of the actions carried out,and provide a joint base to monitor the evolution of ports toward fulfilling the SDGs. Tools such as the Life Cycle Analysis (LCA), Circulytics (From EMF), and Circular Transition Indicators (CTI) (From the wbcsd) support industrial ports' transition towards a more circular business, regardless of complexity and size of operations. These tools are also used to assist companies, consumers, and policymakers in greening their practices and decisions. For example, LCA results can tell us if one product or service is environmentally preferable to another or what aspects of a product or process contribute most to environmental impacts. Circulytics and CTI measures terminals and companies' entire circularity achievements in a more comprehensive way.

Barriers

- *Lack of awareness and organizational cultural barriers*: Particularly a lack of stakeholders or consumer interest and awareness, as well as a weak company culture (integrity and ethics, respect for the environment…), are considered significant CE barriers by businesses and policymakers. Awareness of CE is vital to increase enthusiasm and support, stimulate self-mobilization and action, and mobilize local knowledge and resources. Ports must think strategically when developing circular programs, projects, or initiatives. Integration needs to be at the core of circular developments.
- *Absence of customers and other stakeholders' interests*: In many cases, port stakeholders need to understand the concept of CE in ports and its benefits. Additionally, circular products and actions are more expensive than 'non-circular' goods. These two factors limit consumer demand for circular products or services. Customers and

consumers opt to pay for less expensive products that contribute to carbon emissions.

- *Expensive upfront investments in new business models and taxation systems*: Business transformation in ports is costly. It requires significant investments in energy production facilities, superstructure, and waste management facilities. These include high secondary product costs, and raw materials, as opposed to the often lower cost of virgin resources (partially caused by higher taxes on labor which penalizes reuse, repair, and recycling), and current taxation systems, which tend to reward linear models rather than circular models (value-added tax on upcycled products, for example, requires paying twice for the same product). Policies should promote activities that are desired by society and punish those that are not.
- *Shortage of green infrastructure*: The key is to produce resources like electricity, steel, cement, and meat without any emissions but at the least cost. This approach requires an upgrade of infrastructure. Using more clean energy requires upgrades and suitable financial mechanisms for vehicles, buildings, and port equipment. For example, the Port Authority of Valencia (PAV) has expanded its electric vehicle fleet and added new charging points for employees and visitors (Greenport 2022). Nearly one-third of plastics are not collected by a waste management system and end up as litter in the world's lands, rivers, and oceans. According to the Washington Post, there could be more plastics than fish in the ocean by 2050 (The Washington Post, 2016).
- *Lack of harmonized policies to facilitate the transition to a circular economy*: Effective policies can help accelerate and scale up circular actions in the economy. These policies support businesses in overcoming hurdles by stimulating innovative projects and long-term investments in circularity, facilitating collaboration and partnerships, and producing tangible results. Policies for robust standards and norms in production, expansion of circular procurement, tax relief for circular products, support for eco-industrial parks, and awareness campaigns are essential.
- *The GDP as an indicator of economic activities*: The GDP index does not consider social and environmental externalities, discouraging value creation in both these areas. A new economic model for measuring growth and sustainable development is needed. Policymakers could use 'resource-miser' indicators such as value-per-weight and labor-input-per-weight ratios rather than GDP or others.
- *Lack of better integration (system thinking)*: Ports and companies inside the port look more to economic sustainability than social and environmental sustainability integration. Ports think about producing biofuel but need to see the impact on the food supply. Better integration is needed. This integration is about looking for the planet's harmony and integration to work for the planet.

Level of development of CE practices

The following Table 10 shows the level of application of circular projects for each material flow, High Application (HA), Moderated application (MA) and low application (LA) based on the findings in the research. This rating provides evidence of achieving objective 2 of the research.

Table 10 Maritime port material flows level of application as per research findings

Technical cycle	Related CBM (s)	HA	MA	LA	Examples	Comments
Maintenance	PLE/GSS		X		Buildings/Equipment/Containers/Furniture/Lighting	No major comments in social science journals on how ports are extending the life of these items. Although maintenance is applied, more can be done to use assets longer time
Reuse and share	RRU/SCC/RPO or PSS			X	Share of vehicles and Bicycles for employees/Share of machinery/reuse of part for solar panels and other	Limited examples identified in the literature and quite easy to implement and reinforced
Remanufacturing	PLE/RRU			X	Industrial symbiosis (Textiles/Electronics/Cars/Equipment)	Limited examples identified in the literature. A port is connecting supply chains for the car remanufacturing
Recycling	DFR/GSS		X		Plastic/Waste/Fishing nets/Aluminum/Carton	A few ex for plastic, waste, and fishing nets where identified. There are large quantities of glass, carton or aluminum that are generated in cruise ships that can be recycled in ports
Biological Cycle	**Related CBM(s)**	**HA**	**MA**	**LA**	**Examples**	**Comments**
Extraction of biochemical feedstock	BBB/CMW			X	Biomass plants Biofuel plants	Different ports are in different stages of developing clean energy production
CO2 Capture	BBB/SCC/RRU			X	CCUS or CCS to produce renewable diesel or naphtha (renewable fuels)	Carbon capture technology is a viable strategy to move the industrial and power sectors towards decarbonisation
Cascade	CMW/GSS/BBB			X	Sea by-product use in medicine or food. Automotive and recycling,	Secondary materials from the sea can be used in medicine or added value products
Solid restauration and farming & collection	RRU/SFA/CMW/BBB			X	Agricultural innovation fund, protection of wild life and nature	Regeneration of land to protect the ecosystem is critical for circular economy, cascading and biofuel

Source: By the author

Moving towards a more circular approach could deliver benefits such as reducing pressure on the environment, improving the security of the supply of raw materials, increasing competitiveness, stimulating innovation, and boosting economic growth. It could create approximately 580,000 jobs in the EU alone (European Commission 2019). Carbon Capture is getting much attention and can potentially create chemically identical characteristics to fossil–derived diesel and naphtha (Greenport 2022). People must move forward on CE implementation to allow future generations to meet their needs.

Discussions and conclusions

Circular business models (CBMs) in ports

All generic CBMs identified in Table 3 can be implemented in MIP. Established MIP should regularly update their business plans, or they will need to anticipate trends and challenges ahead. As in other industries, we see continuous re-direction in strategies and innovation in the port that creates new opportunities and revenue streams.

This review identifies over 190 Circular Business Models (CBMs) implementations for various types of circular investments described in Tables 6, 7, and 8. The predominant models for MIP are BBB, RRU, GSS, SCC, and DFR, as detailed in Table 3. This demonstrates the integration between different models.

Circular assets and equipment

This review identified potentially 58 CBM implementations; the predominant models are also GSS, RRU, and SCC in this intervention area. To facilitate the transition to CE, ports can adopt maintenance and innovative asset utilization practices, reducing waste and resource consumption and promoting material reuse and recycling. The ports in Europe have taken actions such as developing sustainable energy sources, optimizing other resource usage, and embracing digitalization for more efficient and sustainable operations. Investments in waste management, clean water, air quality monitoring, and ecosystem protection infrastructure comply with existing and future regulatory requirements.

The development of sustainable energies is considered a RRU and/or BBB CBM(s). Installing solar farms in industrial ports (RRU) also enables creating GSS models when utilizing recycled panels and components. Solar power is increasingly utilized in warehouses and production facilities. A BBB model example is the production of Green Hydrogen, which can be used for manufacturing fertilizers and fuel. The BBB model complements SFA by enabling cleaner fertilizer production and RRU by applying blue hydrogen when capturing and storing CO2. Green hydrogen holds promise in replacing fossil fuels and achieving a net-zero society, the current geopolitical situation favors alternative energy sources and pushes for hydrogen adoption in Europe and other import-dependent markets. Combining energy sources, including green hydrogen, is essential for successfully transitioning to renewable energy. Sustainable energy production has transformative potential for ports and national economies, as demonstrated by Rotterdam and Antwerp's ambitions to become energy hubs through collaboration.

Investing in water monitoring to protect the ecosystem develops SCC and GSS Business Models. For instance, North Sea ports utilizes smart sensors to monitor water parameters, anticipating water quality issues continuously. Such actions contribute to circularity by regenerating ecosystems. Environmental sustainability efforts like tree planting, coastal cleaning, and bird protection restore ecosystems and mitigate climate change while generating SFA and CMW CBMs. Rotterdam, Denmark, Piombino, and Dover ports have implemented these actions and offer potential for replication in other industrial ports. Climate change is No 1 priority now and these actions are critical.

Responsible digitalization is important in accelerating the transition to a CE and achieving global climate goals by 2050. For example, the Port of Haminakotka in Finland employs Virtual 3D operating systems to streamline operations, identify damages, and improve stakeholder communication. Digitalization allows for implementing SCC, and DFR CBMs. The port can share the operating system with industries in the Mussalo industrial zone, enhancing design for durability and recycling. 3D technology can significantly reduce material waste and contribute to Greener Supply Chains in any type of industry.

To support a sustainable energy transition, port environmental facility development, and digitalization, regional finance institutions like the European Investment Bank, African Development Bank, Inter-American Development Bank, and governments can provide financing for scalable technologies and adopt international regulations guided by circular principles.

Circular flows within the port

This review identified potentially 56 CBM implementations; the predominant models are GSS, RRU, and SCC in this intervention area. The ports identified in this study are recovering, recycling, or upcycling plastic, CO2, sand, sediments, old stables, methane, heat, rainwater, and shipping containers for other valuable uses (cascading or upcycling). Better management of waste generated by industrial ports is another area where ports can facilitate the transition to CE. Plastic reduction, recycling, and segregation of industrial ports (including industrial zones and ships as indicated in this project's scope) create RRU and GSS opportunities. These models work in collaboration and facilitate the adoption of other models, such as SFA, DFR, and SCC.

Amsterdam and Rotterdam have plastic recycling facilities using Magnetic Density Separation (MDS). They transform recyclable plastic into raw materials for new plastics. In contrast, non-recyclable plastics are converted into transport fuel by cooperating with other companies in the port, becoming a real circular plastic hub. At least 14 million tons of plastic end up in the ocean yearly, making up 80% of all marine debris from surface waters to deep-sea sediments (IUCN 2021). Plastic recycling facilities can allow ports to manage plastic waste flows and improve collaboration.

Critical circular developments in ports are on CCUS or CCU, which creates SCC, and RRR. Approximately 26 commercial-scale carbon capture projects are operating worldwide, with 21 more in early development and 13 in advanced development (Center for Climate and energy solution 2020). Carbon Capture infrastructure is essential for Europe climate plans. Singapore Economic Development Board recently mentioned that the island aims to realize at least 2 million tons of carbon capture potential by 2030 as part of a broader effort to make its Jurong Island oil refinery hub more sustainable (Reuters 2021).

Former waste streams from the fishing industry are being used to manufacture a range of high-value products in the nutrition and beauty industry. This approach developed cascades in the biological cycle of great interest for CE, more cascading CBMs need to be initiated and documented. Innovation is a crucial driver for circular practices. Biofuels, CCU, sustainable environment terminals, and offshore energy provision are just a few initiatives that require implementing state-of-the-art technology. If the technical flow does not considered new technologies, it is impossible to increase plastic recycling rates, maintain assets functioning for longer, or redesign products to be more durable.

Port and circular markets

This paper identified 84 CBM implementations for circular initiatives or projects running; the most predominant are GSS, RRU, SCC, and PLE in this intervention area. The port is critical as an engine to incentivize and force circular and sustainable practices. Ports can promote and encourage stakeholders to be more circular by developing new activities connecting supply and demand. Main initiatives and projects found to develop circular markets are establishing eco-parks and developing industrial symbiosis (IS), settling shipyards in their premises for building or decommissioning ships, sharing mechanical equipment, extending the life of parts and raw materials (for cars and other industries) by linking industries and providing logistics services, and creating upcycling factories. In addition to opening dialog with stakeholders to support environmental and circular projects, implementing several financial incentives are potent mechanisms to create circularity.

Under this area of intervention, one of the main goals should be the development of IS by developing Eco-Parks, these Eco-parks are a powerful mechanism for the sustainable use of environmental resources. It promotes the development of all CBMs, initiating with SCC. IS encompasses initiatives in which two or more industries develop mutually beneficial relationships. Other examples of synergetic cooperation include the shared utilization of specific equipment or facilities and the pooling of resources. Kalundborg, Rotterdam, and Harjavalta are some examples of Eco-parks identified. IS promotes economic growth while, at the same time, it generates environmental benefits. Implementation of IS, therefore, holds potential to unlock powerful mechanisms that foster sustainable development (Chertow 2007).

Extending the life of spare parts or materials for the car industry in Belgium adds value to customers and contributes to circularity. This life extension is possible by providing logistics services linking where products are used with where specialist knowledge is available. These develop RRU, PLE, and DFR CBMs. The replication of such practices in the port to enable car business symbiosis can be replicated in other shipping industries. Having shipbuilding and decommissions operations in industrial ports is a critical circular enabler. These industries will ensure responsible ship recycling or refurbishing, reducing energy and CO2 emissions. This business promoted RRU, and DFR CBMs. Today's value chain and its incentives in this market are reconfigured through a circular ships initiative. The industrial ports of Parema, Alveiro, Gdansk, and Palma have shipyards on their premises, also promoting sustainability.

Ships generate much waste from their large day-to-day operations; various biological wastes can be used well as biogas. Most technical waste, such as paper or aluminum, can be recycled in port facilities generating economy and environment benefits. For example, Costa Cruises projects to reduce waste by more than 70 percent by 2030. If facilities are developed in ports, CO2 from ships, equipment, or plants can be captured and stored in the port contributing positively to the climate change, priority number one of ESPO ports.

Cascading is an underexplored area; secondary materials from the sea can be used in medicine or added-value products. Cascading turns waste streams into new products and can be applied to both cycles but especially in the biological. For example not just the meat can be use from a fish, all anatomic parts could be also used for medical or skin care treatments. Ports in Finland and Germany are providing incentives to shipping companies to upgrade fuel systems to be more eco-friendly and implement sustainable practices such as reducing noise levels; this is based on the "Environmental Ships Index (ESI). These regulations enable sustainable practices and potentially create GSS and BBB CBMs.

Conclusions

This study examines circular practices in ports, identifying 53 practices aligned with CE principles. These practices can lead to the developing of 231 different circular business models (CBMs). The study highlights CBMs for three areas of intervention, including bioenergy and biomass production, resource recovery and recycling, green supply services, sharing models, and product life extension. Ports increasingly invest in clean energies like wind and solar power to reduce greenhouse gas emissions and support green supply services. Waste management infrastructure and technologies, such as recycling facilities and advanced wastewater treatment systems, are being implemented to address environmental sustainability. Recycling, reuse, and repair practices are gaining traction, promoting circular CBMs. Critical drivers for CE implementation in ports include a circular vision, disruptive technology, incentives, partnerships, and tracking measures. In contrast, barriers include organizational culture, lack of awareness, policy harmonization, and upfront investments. The study suggests moderate to low implementation levels of circular activities, highlighting the need for improvement. Adopting CE principles in ports can transform the linear model, benefiting the environment, economy, and stakeholders. Successful implementation requires collaboration, system thinking, and overcoming regulatory barriers.

Abbreviations

BBB	Bioenergy, biomass and biochemical production
CCU	Carbon capture utilization
CCUS	Carbon capture utilization and storage
CMW	Cascading for medical and wellness
CBMs	Circular business models
CE	Circular economy
CTI	Circular transition indicators
DOD	Delivery on demand
DFR	Design for recycling
EMAS	Eco-management and audit scheme
EC	European Commission
ESPO	European Sea Ports Organization
EU	European Union
GSS	Green supply service
IS	Industrial Symbiosis
IZ	Industrial zones

IAPH	International Association of Port and Harbors
LCA	Life cycle analysis
LE	Linear economy
MIP	Maritime industrial ports
OECD	Organization for economic cooperation and development
PA	Port authority
PERS	Port environmental review system
PSS	Product as a service
PLE	Product life extension
RRU	Recycle and upcycle
RRU	Resource recovery, recycle and upcycle
RPO	Retain product ownership
SDM	Self diagnosis method
SSLR	Semi-systematic literature review
SCC	Sharing collaborative and consumption
SFA	Sustainable food, agriculture and aquaculture
SDGs	United Nations Sustainable Development Goals
WBCSD	World business council for sustainable development

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Author contributions
JB carry out the study with the supervision of FB and MC technically and methodological. JB was the major contributor to the writing with the important feedback and contribution of FB and the editing of MC.

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References
Accenture (2015) Waste to wealth–5 business models to circular economy. Retrieved from accenture newsroom: https://newsroom.accenture.com/news/the-circular-economy
Andersen M (2007) An introductory note on the environmental economics of the circular economy. Sustain Sci 2:133-140
Awan U, Sroufe R (2022) Sustainability in the circular economy: insights and dynamics of designing circular business models. Appl Sci 12(3):1521
Ayres RU, Ayres L (eds) (2002) A handbook of industrial ecology. Edward Elgar Publishing
Babbitt CW, Althaf S, Rios FC, Bilec MM, Graedel TE (2021) The role of design in circular economy solutions for critical materials. One Earth 4:353–362
Baden-Fuller C (2010) Business models as models. Long Range Plan 43(2–3):156–171
Bakker CA, den Hollander MC, van Hinte E, Zijlstra Y (2014) Products that last: product design for circular business models. TU Delft Library
Barnet J (2003) Security and climate change. Glob Environ Change 13:7-17
Barros MV, Salvador R, do Prado GF, de Francisco AC, Piekarski CM (2021) Circular economy as a driver to sustainable businesses. Clean Environ Syst 2:100006
Bexel M, Jonsson K (2017) Responsibility and the United Nations' sustainable development goals. Forum Dev Stud pp 13–19
Beynus J (2002) Biomimicry: innovation inspire by nature. Harper Collins
Bianchini A, Rossi J, Pellegrini M (2019) Overcoming the main barriers of circular economy implementation through a new visualization tool for circular business models. Sustainability 11:6614
Biwei S, Heshmati A, Geng Y, Yu X (2012) A review of the circular economy in China: moving from rhetoric to implementation. J Clean Prod 42:215–227

Bioregional (2017) Cracking the circular challenge. https://storage.googleapis.com/www.bioregional.com/downloads/Cracking-the-circular-challenge_Bioregional_2017_circular-economy.pdf
Bocken NMP, Rana P, Short SW (2015) Value mapping for sustainable business thinking. J Ind Prod Eng 32(1):67–81
Bocken NM, Short SW (2016) Towards a sufficiency-driven business model: experiences and opportunities. Environ Innovat Soc Trans 18:41–61
Bonciu F (2014) A more prosperous europe: revisiting the concept of growth, development and prosperity. Roman J Euro Affairs https://EconPapers.repec.org/RePEc:rjr:wpconf:141109
Bonciu F (2020) Is circular economy compatible with capitalism? Romania Econ Bus Rev, pp 16–30
Brais Suarez E, Fernandez E, Mendez G, Soto D (2019) Operational principles of circular economy for sustainable development: Linking theory and practice. J Clean Prod 214:952–961
Braun V, Clarke V (2008) Using thematic analysis in psychology. Qualit Res Pshycol 3(2):77–101
Braungart M, McDonough W (2002) Cradle to cradle. Random House
Bull SR (2001) Renewable energy today and tomorrow. Proceedings of the IEEE, p 8
Calvo N (2018) Multi-industrial ports: understanding interactions and identifying development opportunities
Cardoso M (2022) Circular economy strategy and waste management: a bibliometric analysis in its contribution to sustainable development, toward a post-COVID-19 era. Environmentla Science and Pollution research
CE Parcticioner Guide (2018) Dispose Cascading. Retrieved from World Business Ccouncil for Sustainable Development - wbcsd: https://www.ceguide.org/Strategies-and-examples/Dispose/Cascading#:~:text=Cascading%20maximizes%20resource%20effectiveness%20by,and%20services%20have%20been%20exhausted.
Center for Climate and Energy Solution. (2020) Carbon capture. Retrieved from C2ES: https://www.c2es.org/content/carbon-capture/#:~:text=Carbon%20capture%20use%20and%20storage,large%2Dscale%20CCUS%20facilities%20operating%20%E2%80%A6
Chertow MR (2007) "Uncovering" industrial symbiosis. J Ind Ecol 11(1):11–30
Christodoulou A, Cullinane K (2019) Identifying the main opportunities and challenges from the implementation of a port energy management system: a SWOT/PESTLE analysis. Sustainability
Accenture (2014) Circular advantage. https://www.accenture.com/t20150523t053139__w__/us-en/_acnmedia/accenture/conversion-assets/dotcom/documents/global/pdf/strategy_6/accenture-circular-advantage-innovative-business-models-technologies-value-growth.pdf
Circular Ecology (2015) Sustainability and sustainable development–what is sustainability and what is sustainable development? Retrieved from Circular ecology https://circularecology.com/sustainability-and-sustainable-development.html#::text=This%20is%20also%20known%20as,sustainability%20factors%20in%20equal%20harmony.&text=Environmental%20Sustainability%3A%20Environmental%20sustainability%20means
Clift R, Druckman A (2016) Taking stock of industrial ecology. Springer, New York
Cohen S (2022) Fossil fuels, renewable energy, and electric vehicles. State Planet
COP26 (2021) Sustainability. Retrieved from un climate change conference UK26 https://ukcop26.org/the-conference/sustainability/
Devinka K (2020) Sustainable circular supplier selection: a novel hybrid approach. Sci Total Environ 722:137936
European Commission (2019) Circular economy action plan. Sited by the European Commission. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en#:~:text=The%20new%20action%20plan%20announces,for%20as%20long%20as%20possible
Eckard, H, Walker P (2021) We must rapidly decarbonise road transport–but hydrogen's not the answer. Retrieved from The Driven: https://thedriven.io/2021/11/19/we-must-rapidly-decarbonise-road-transport-0-but-hydrogens-not-the-answer/amp/#aoh=16376362500920&csi=0&referrer=https%3A%2F%2Fwww.google.com&amp_tf=From%20%251%24s
Circle Economy (2018) The Circularity Gap Report. https://pacecircular.org/sites/default/files/2020-01/Circularity%20Gap%20Report%202018_0.pdf
Ellen MacArthur Foundation (2019) Completing the picture, how the circular economy tackles climate change. Sited by the Ellen MacArthur Foundation. https://circulareconomy.europa.eu/platform/sites/default/files/emf_completing_the_picture.pdf
Ellen MacArthur Foundation (2021) Completing the picture, how the circular economy tackles climate change. Sited by the Ellen MacArthur Foundation. https://emf.thirdlight.com/file/24/XoGiOySXvopGQ9Xo4d6XnKIvUh/Completing%20the%20picture%20-%20%20Executive%20summary.pdf
Ellen MacArthur Foundation–School of Thoughts (2023) Ellen Macarthur foundation. Retrieved from Schools of thought that inspired the circular economy. https://ellenmacarthurfoundation.org/schools-of-thought-that-inspired-the-circular-economy
EMF (2014) Towards the circular economy
EMF (2017) Towards a circular economy: Business rationale for an accelerated transition. Retrieved from Ellen Macarthur foundation: https://ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition
Ellen MacArthur Foundation (2019, February) . Circular Economy System Diagram. Sited by Ellen MacArthur Foundation. https://emf.thirdlight.com/link/7kvazph93afk-owveai/@/preview/1?o
Ellen MacArthur Foundation (2020) What is the linear economy? Retrieved from Ellen macarthur foundation: https://ellenmacarthurfoundation.org/what-is-the-linear-economy
Environmental Performance Index (2020) Environmental performance index. Columbia University
European Sea Port Organization (2020) Retrieved from Energy and fuel. https://www.espo.be/practices?tag=energy-fuels
European Sea Port Organization (2021, October). ESPO Environmental Report, EcoPortsinSights. ESPO Secretariat.
ESPO (2023) ESPO—home. Retrieved from ESPO.be: https://www.espo.be/
European Commission (2015) Closing the loop—an EU action plan for the circular economy
European Commission (2019) The European green deal. European Commission, Brussels
European Commission (2020) Circular economy action plan for a cleaner and more competitive Europe. European Union

European Commission (2020) EU Science Hub. Retrieved from Sustainable Product Policy: https://joint-research-centre.ec.europa.eu/scientific-activities-z/sustainable-product-policy_en#:~:text=It%20is%20estimated%20that%20over,throughout%20their%20entire%20life%20cycle.
European Commission (2021) European green deal: commission proposes transformation of EU economy and society to meet climate ambition European Commission - Press Release Brussels
European Commission (2021) Is the Fit for 55 package really fit for purpose? Brussels
European Commission (2021) What is the bioeconomy and how could it help fight climate change? The EU research & Innovation Magazine: EU Commission
European Council (2021) Fit for 55. Retrieved from European Green deal: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/
European parliament (2022, February, 12) Circular economy: definition, importance and benefits. Retrieved from European parliament News: https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits
Eurostat (2022, September, 22) Amount of waste recoverred increases in 2020. Eurostat news
Eurosta (2022, 09 13) Asset Publisher—-products Eurostat Mews
Eurostat News (2022, September, 13) Asset Published-Products Eurostat News
Figueres C (2021) Retrieved from Sustainable World Ports: https://sustainableworldports.org/
Fisker J, Graedel T, Hecht A (2009) EPA at 40: Bringing Environmental Protection into the 21st Century. Environ Sci Technol 43(23):8716-8720
FISSAC (2016) Identification of best practices and lessons learned in industrial symbiosis. European Commision Horizon 2020 for research and innovation under grant agreement No 642154
Dwarakisha GS, Akhil S (2015) Review on the role of ports in the development of a nation. Aquatic Procedia 4:295–301
Gardetti MA (2019) Introduction and the concept of circular economy. In: Circular economy in textiles and apparel. Woodhead Publishing, pp 1–11
Geissdoerfer M, Savaget P, Bocken NM, Hultink EJ (2016) The circular economy: a new sustainability paradigm? J Clean Product 143:757–768
Geng Y, Doberstein B (2008) Developing the circular economy in China: challenges and opportunities for achieving 'leapfrog development'. Int J Sustain Dev World Ecol 15(3):231–239
Ghisellini P, Cialani C, Ulgiati S (2016) A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J Clean Prod 114:11–32
Ghodke PK, Sharma AK, Moorthy K, Chen WH, Patel A, Matsakas L (2022) Experimental investigation on pyrolysis of domestic plastic wastes for fuel grade hydrocarbons. Processes 11(1):71
Giampietro M, Ramos J, Bukkens S, Martinez J, Van der Velden I (2020) Sustainability science: an overview through the lens of scopus. J Sustain
Glarini O (1989) The limits to certainty: facing risks in the new service economy. Kluwer Academic, Dordrecht
Graedel T, et al (1994) Industrial ecology and global change. Cambridge University Press
Green Hydrogen System (2021) Accelerating the global energy transition with green hydrogen. Retrieved from Green Hydrogen System https://greenhydrogen.dk/
Green Port Initiative (2023) Green port initiative. Retrieved from EIPA: https://www.eipa.eu/epsa/green-port-initiative/
Green M (2019 Sept 24) We are 43 years behind schedule on achieving the SDGs, and the US is going backwards'. Retrieved from Reuters Events: https://www.reutersevents.com/sustainability/we-are-43-years-behind-schedule-achieving-sdgs-and-us-going-backwards
Greenport (2022) Greenport Autum 2022. Greenport. Belgium
Griggs D (2013, March 21) Sustainable development goals for people and planet. Nature 495:305–307
Guide D, Wassenhove L (2009) The evolution of closed-loop supply chain research. Oper Res 57(1):10–18
Guillaume M (2013) Industrial symbiosis and Eco-Industrial parks—best practices in the European union. Brussels. Retrieved from file:///C:/Users/jbarona/Downloads/sif-2013may27-guillaume-massard-sofies_en%20(2).pdf
Gurel E, Tat M (2017) SWOT Analysis_ATheoretical Review. Retrieved from http://hdl.handle.net/10673/792
Haezendonck E, van den Berghe K (2020) Patterns of circular transition: what is the circular economy maturity of belgian ports? Sustainability
Harvard Business Review (1994) The challenge of going green. Retrieved from Harvard Business Review: https://hbr.org/1994/07/the-challenge-of-going-green
Harvard Business Review (2021, August) Harvard Business Review. Retrieved from The Circular Business Model: https://hbr.org/2021/07/the-circular-business-model
Harvard Business Review (2021, July) The circular business model. Harvard Business Review
Heikkila M, Saarni J, Saurama A (2022) Innovation in smart ports: future directions of digitalization in container ports. Marine Sci Eng 10(12):1925
Hirscher M, Autrey T, Orimo S-I (2019) Hydrogen Energy
Hu B, Lirn T (2016) Green port: development, challenges and opportunities. J Clean Prod
IAASTD (2008) IAASTD. Island Press
IEA (2020) Energy technology perspectives. IEA
IMO (2020) Reception facilities. Retrieved from Marine Environment: https://www.imo.org/en/OurWork/Environment/Pages/Port-Reception-facilities.aspx
International Energy Agency (2020) Global status report for building and construction. UN
International Energy Agency (2021) Net Zero By 2050–a roadmap for the global energy sector. IEA
IUCN (2021, November) Marine plastic pollution. Retrieved from Internatinal Union for Conservation or Nature: https://www.iucn.org/resources/issues-briefs/marine-plastic-pollution#:~:text=At%20least%2014%20million%20tons,causes%20severe%20injuries%20and%20death.
Hopkins J (2021) Renewable energy vs sustainable energy_what's the difference? Johns Hopkins School of Advance International Studies

Kalmykova et al (2018) Circular economy: from review of theories and practices to development of implementation tools. Resour Conserv Recycl 135:190–201
Kaza et al (2018) What a waste: a global snapshot of solid waste management to 2050. Washington: World Bank
Kenneth B (1966) The economics of the coming spaceship earth.
Kirchherr, et al (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 127:221–232
Korhonen J, Honkasalo A, Seppala J (2016) Circular economy: the concept and its limitations. Ecol Econ 143:37–46
Kritchherr J, et al (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Concer Recycl 127:221–232
Kuhlman T, Farrington J (2010) What is sustainability? Sustainability
Kusch S (n.d.) Industrial symbiosis: powerful mechanisms for sustainable use of environmental resources
Lacey P, et al (2015) Waste to wealth: the circular economy advantage. 1st
Langen P, Henrik F, 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(11):4397
Lieder M, Rashid A (2016) Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J Clean Prod 93:1953–1970
Liu X (2020) Research on the (positive) externality of ports
Loivins AB, Lovins H, Hawker P (1999) A road map for nature capitalism
Loop port (2018) Circular economy network of ports–loop port
LOOP Ports (2018) Circular economy network of ports
Loop ports (2023) Loop ports—-circular economy network of ports. Retrieved from Loop Port Overview: https://www.loop-ports.eu/about/overview/
McDonough W, Braungart M (2002) Cradle to cradle. Random House
Meidle R (2021, August 3) A circular economy does not necessarily translate to sustainability. Retrieved from Forbes: https://www.forbes.com/sites/thebakersinstitute/2021/08/03/a-circular-economy-does-not-necessarily-translate-to-sustainability/?sh=340a41b361a7
Menegaki A (2007) Valuation for renewable energy: a comparative review. Renew Sustain Energy, pp 2422–2437
METI (2004) Handbook on resource recycling legislation and 3R initiatives
Mikael L (2020) Sustainable ports as energy hubs
Mindtools (2020) SWOT analysis. Retrieved from MindTools: https://www.mindtools.com/pages/article/newTMC_05.htm
Mongabay (2022, Sept 8) We've crossed four of nine planetary boundaries. What does this mean? Mongabay, News & Inspiration from nature's frontier
Monios J, Woxenius J (2020) Port centric logistics. J Trans Geograph
Mud Jeans (2020) Mud Jeans. Retrieved from Creating a world without waste: https://mudjeans.eu/pages/our-mission-about-us
Rockstrom J (2009) A safe operating space for humanity. Nature 461:472–475
Neves A, Godina R, Azevedo SG, Matias J (2019) A complrehensive review of industrial symbiosis. J Cleaner Prod 247
Nikolaou I, Evangelinos K (2010) A SWOT analysis of environmental management practices in Greek Mining and Mineral Industry Resour Policy 35:226–234
T Notteboom A Pallis J-P Rodrigue 2022 POrt economics management and policy Routledge New York
O'Neill DW (2018) A good life for all within planetary boundaries. Nat Sustain 1:88–95
OECD (2018) Business models for the circular economy: opportunities and challenges from a policy perspective. OECD Publishing, Paris
OECD (2019) BUsiness MOdels for the CE
Patwa N (2021) Towards a circular economy: an emerging economies context. J Bus Res 122:725–735
Pearce D, Turner R (1990) Economics of natural resources and the environment. Johns Hopkins University Press, Baltimore
Personsova A, Machar I (2021) National limits of sustainability: the Czech Republic's CO2 emissions in the perspective of planetary boundaries. Sustainability 13(4):2164
Petticrew M, Roberts H (2006) Systematic reviews in the social sciences: a practical guide. Blackwell Publishing Ltd., Victoria
Philipp R (2020) Digital readiness index assessment towards smart port development. Sustain Manage Forum 28:49–60
Pieroni MP, McAloone TC, Pigosso DC (2018) Business model innovation for circular economy and sustainability: a review of approaches. J Clean Prod, pp 198–216
Planet Ark (2020, October 21) Three core principles of the circular economy. Retrieved from Planet Ark: https://planetark.org/newsroom/news/three-core-principles-of-the-circular-economy
Popp J, et al (2014). The effect of bioenergy expansion: food, energy, and environment. Renew Sustain Energy Rev, pp 559–578
Port of Haminakokta (2018) The world's most intelligent digital seaport. Retrieved from Port of Haminakotka: https://www.haminakotka.com/current-issues/worlds-most-intelligent-digital-seaport
Port of Rotterdam (2023) Port of rotterdam. Retrieved from Industry in the port: https://www.portofrotterdam.com/en/setting/industry-port
Purvis B, et al (2019) Three pillars of sustainability: in search of conceptual origins. Sustin Sci 14:681–695
RM (2021, August 3) A circular economy does not necessarily translate to sustainability. Retrieved from Forbes.com: https://www.forbes.com/sites/thebakersinstitute/2021/08/03/a-circular-economy-does-not-necessarily-translate-to-sustainability/
Rabaina M, Villar J, Pereira E (2020) The determinants for a circular economy in Europe. Environ Sci Pollut Res Int 27(11):12566-12578
Rakhyun K, Kotze L (2021) Planetary boundaries at the intersection of earth system law, science and governance: a state-of-the-art review. Rev Eur Commun Int Environ Law 30(1):3–15
Ravango M, et al (2015) The principles and practice of sustainable economic development: overview and synthesis. Sustain Econ Dev 3–10

Raworth K (2018, April 11) Why we need to move toward an economy that can regenerate itself. Retrieved from Ideas. Ted.Com: https://ideas.ted.com/why-we-need-to-move-toward-an-economy-that-can-regenerate-itself/
Renault Group (2017, Mar) Renault, actively developing circular economy throughout vehicles life cycle. Retrieved from Renault Group: https://www.renaultgroup.com/en/news-on-air/news/renault-actively-developing-circular-economy-throughout-vehicles-life-cycle/
Reuters. (2021, November 23) Singapore targets 2 mln tonnes of carbon capture by 2030. Sustain Bus
Roberts T (2021) A virtuous circle? Increasing local benefits from ports by adopting circular economy principles. Sustainability
Roberts T, Williams I, Peterson J, Clarke N, Odum M, Gorman SO (2021) A virtuous circle? Increasing local benefits from ports by adopting circular economy principles. Sustainability. https://doi.org/10.3390/su13137079
Rockstrom J (2009) Planetary boundaries: exploring the safe operating space for humanity. Ecol Soc 14(2):32
Rockstrom J, Stefan W (2009) A safe operating space for humanity
Rossi E, Bartassini AC, Ferreira C (2020) Circular economy indicators for organizations considering sustainability and business models: plastic, textile and electro-electronic cases. J Clean Prod 247:119137
Samsara (2021, November 3) How are electric vehicles better for the environment? Retrieved from Samsara: https://www.samsara.com/guides/how-are-electric-vehicles-better-for-the-environment/
Schroder P, Raes J (2021, July 19) Financing an inclusive circular economy. Retrieved from Chatham House: https://www.chathamhouse.org/2021/07/financing-inclusive-circular-economy/02-sdgs-and-how-circular-economy-finance-can-0
Scopus (2021) Welcome to scopus preview. Retrieved from Scopus Preview: Welcome to Scopus Preview
SDGS (2021) Goal 12. Retrieved from Sustainable development goals: https://www.un.org/sustainabledevelopment/sustainable-consumption-production/
SDGs Report (2020) The SDGs Report. UN
Sehnem S, et al (2018) Circular economy: benefits, impacts and overlaping. SCM Int J. https://doi.org/10.1108/SCM-06-2018-0213
Shipper C, Vreugdenhil H, de Jong M (2017) A sustainability assessment of ports and port-city plans: comparing ambitions with achievements. Trans Res D, pp 84–111
Singh J, et al (2019) Evaluating approaches to resource management in consumer product sectors—an overview of global practices. J Clean Prod 224:218–237
Snyder H (2019) Literature review as a research methodology. J Bus Res 104:333–339
Sohar port (2023) Sohar port. Retrieved from Sohar port and free zone: https://soharportandfreezone.om/en/who-we-are/about-sohar
Stahel W (2008) Global climate change in the wider context of sustainability. The international association for the study of insurance. Economics, pp 507–529
Stahel WR (2016, March 24) Circular economy: a new relationship with our goods and materials. Comment
Stanhel W, et al (1976) The potential for substituting manpower for energy, report to the Commission of the European Communitie.
Stanhel W, Redal G (1981) The potential for substituting manpower for energy: a report to the European Commission
Stefanakis AI (2020) How to achieve sustainability? Through circular economy. Retrieved from Spting News: https://sustainabilitycommunity.springernature.com/amp/posts/how-to-achieve-sustainability-through-circular-economy
Stehel W (2010) The performance economy, 2nd edn
Stevens C, Kanie N (2016) The transformative potential of the Sustain Dev Goals. Int Environ Agreements 16:393–396
Su B, et al (2013) A review of the circular economy in China: moving from rhetoric to implementation. J Clean Prod 42:215–227
Surmen Y (2002) The necessity of biomass energy for the Turkish Economy
SWP (2021) About the program. Retrieved from WPSP: https://sustainableworldports.org/
Tan E, Llamers P (2021, July 12) Circular bioeconomy concepts—a perspective. Frontiers in sustainability
Taylor L (2020, October 14) What is the linear economy and why do we need to go circular? Retrieved from Planetark: https://planetark.org/newsroom/news/what-is-the-linear-economy-and-why-do-we-need-to-go-circular
The Washington Post (2016, January 20) By 2050, there will be more plastic than fish in the world's oceans, study says. The washington post. https://www.washingtonpost.com/news/morning-mix/wp/2016/01/20/by-2050-there-will-be-more-plastic-than-fish-in-the-worlds-oceans-study-says/.
The World Bank (2018) What a waste 2.0. Washington: World bank
The World Bank (2022) Port reform toolkit PPIAF, World Bank, 2nd edn
The World Bank (2022). WB Glossary of port and shipping terms
The World Counts (2021) The world counts. Retrieved from https://www.theworldcounts.com/search?target=counters&query=Bow%20many%20earth%20we%20need
Tiana A, Rosa LR, Quatglas C (2020) Circular economy business models: a systematic literature review and future research directions. Sustainability
Totaro A (2021, July 13) What does it take to make a car truly circular? Retrieved from GreenBiz: https://www.greenbiz.com/article/what-does-it-take-make-car-truly-circular#:~:text=and%20its%20use.-,The%20adoption%20of%20circular%20economy%20practices%2C%20combined%20with%20electrification%2C%20has,80%25%20per%20mile%20by%202030.
Tshidimba D (2020, January 14) Roland Berger. Retrieved from Closing the Loops on the Circular Economy: https://www.rolandberger.com/en/Insights/Publications/Closing-the-loop-on-the-circular-economy.html
Tzu Chi Culture & Communication Foundation (2022, Sept 15) Rotterdam: the smartest port in the world. Tzu Chi Culture and Communication Foundation.
UN (1987) Our common future
UN (2015) 6 Clean water and sanitation. Retrieved from Sustainable Development Goals https://www.un.org/sustainabledevelopment/water-and-sanitation/
UN (2018) The 2030 Agenda for sustainable development. Santiago

UN (2019, June 17) Growing at a slower pace, world population is expected to reach 9.7 billion in 2050 and could peak at nearly 11 billion around 2100. Retrieved from Department of Economic and Social Affairs: https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html
UN. (n.d.). Clean water and sanitation: Why Water Matters
UN Environmental Porgram (2019) Emissions gap report. UN
UNCTAD (2019) Circular economy. Retrieved from UNCTAD Prospery for all: https://unctad.org/topic/trade-and-environment/circular-economy
UNCTAD (2020) Review of maritime transport UN Publications New York
UNGA (2018) Circular economy for the SDGs: from concept to practice
United Nationa (2018, June 5) Singl eUse plastic—a roadmap for sustainability. United Nations Environ Program
United Nations (2021) UNFPA. Retrieved from The World Population Dashboard: https://www.unfpa.org/data/world-population-dashboard
United Nations (2021b) United nations. Retrieved from United Nations: https://www.un.org/en/academic-impact/sustainability
US Environmental Portection Agency (2015) Economics of Biofuels
Valenturf A, et al (2019) Circular economy and the matter of integrated resources. Sci Total Environ 689:963–969
Velenturf AP, Purnell P (2017) Principles for a sustainable circular economy. Sustain Prod Consum 27:1437–1457
Velenturf APM, Purnell P, Jenssen P (2021) Reducing material criticality through circular business models: challenges in renewable energy. One Earth, pp 350–352
Von der Leyen U (2019, December 11) The European Green deal. Brussels
WB (2018) What a waste. Washington
Wbcsd (2015) CEO guide to the CE
wbcsd (2017) Circular economy and environmental prioritie for business. WBCSD, Geneva
wbcsd (2020) Circular Economy Action Plan (CEAP) 2020 summary for business: implications and next steps Switzerland
WCED (1987a) Our common future
WCED (1987b) Our common future. UN, Geneva
Webster K (2015) The circular economy: a wealth of flows, 2nd edition
Weetman C (2020) A circular economy handbook. In: Weetman C (ed) A circular economy handbook, 2nd edn. Kogan Page Ltd.
C Wegener 2016 Upcycling Springer
Wierzbicka EM (2021) Circular economy: advancement of European Union countries. Environmental Science Europe
Wild S (2021, June 08) What is the bioeconomy and how could it help fight climate change? Retrieved from European Commission: https://ec.europa.eu/research-and-innovation/en/horizon-magazine/what-bioeconomy-and-how-could-it-help-fight-climate-change
Wong G (2013) RAMESES publication standards: meta-narrative reviews. BMC Med 11(5):20
World Bank (2018) What a waste. The World Bank
World Commission on Environment and Development (1987) Our common future UN Geneva
WPSP (2020) World ports sustainability report. WPSP
WPSP (2021) About the program. Retrieved from WSPS: https://sustainableworldports.org/about/
Yuan Z, et al (2008) The circular economy: a new development strategy in China. J Ind Ecol 10(1–2):4–8

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