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Circular Economy Principles for the Maritime Industry: Increased Value Extraction from End-Of-Life Marine Assets

by

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Signed: Date:

To my loving wife, Deniz,

Thank you for your endless support and for standing by my side through every challenge. I dedicate this work to you, with my deepest gratitude.

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Abstract

The maritime industry, responsible for over 80% of global trade, lags behind other transportation sectors in adopting circular economy (CE) principles, which are essential for enhancing sustainability and reducing environmental impact. This thesis addresses this gap by developing a comprehensive circularity framework tailored specifically to the maritime industry, focusing on four key areas.

First, it identifies the barriers to implementing CE practices in the maritime sector through an extensive literature review and stakeholder engagement. By consolidating insights from surveys, interviews, and workshops, the study uncovers challenges such as regulatory gaps, limited digital infrastructure, and a lack of awareness among stakeholders. Moreover, it highlights the potential benefits of circular applications such as remanufacturing, reuse, and recycling, drawing comparisons to more advanced CE practices in the aviation and automotive industries. These insights underscore the urgency for the maritime industry to embrace circularity to minimise waste and unlock new revenue streams.

Second, the thesis presents strategy and technology solutions suited to the unique operational environment of the maritime industry. The solutions were developed based on identified barriers and validated through case studies and best practices from major OEMs. A case study on high-speed marine engine remanufacturing is provided to demonstrate the practical benefits of circular practices. The study shows that remanufactured engines can deliver equivalent performance to new engines at nearly 50% of the cost, offering significant financial savings while promoting sustainability. This real-world example illustrates the potential for circular practices to reduce costs and environmental impacts across the maritime sector.

Third, the research introduces a first-of-its-kind digital database designed to bridge the valuable equipment tracking and supply chain management gap. The developed database supports a maritime-specific asset tracking system, facilitating fast and transparent information flow between the stakeholders and providing foundations for asset tracking infrastructure and a robust reverse supply chain. Through its practical

application in a case study, the research demonstrated that this system could increase the recovery value of end-of-life vessels by over 80%. The database also facilitates a maritime asset tracking (MAT) system, enabling enhanced transparency and coordination in CE practices. This offers a critical tool for addressing the inefficiencies of reverse supply chains and supporting the industry's transition toward circularity and sustainability.

Finally, the thesis develops 59 tailored circularity metrics specifically designed for the maritime industry. These metrics, refined from hundreds of existing metrics from the literature, provide a comprehensive framework for maritime stakeholders to assess, monitor, and improve their circularity performance. Validated through stakeholder workshops and tested in three shipyards, the metrics offer practical guidance on enhancing circularity efforts. The research findings provide a roadmap for integrating CE principles into the maritime sector, enabling stakeholders to track progress, share best practices, and drive the transition towards a more sustainable and resource-efficient industry.

This thesis, therefore, represents the first comprehensive maritime circularity framework. By addressing gaps in knowledge, proposing tailored solutions, and validating findings through empirical evidence, it offers actionable strategies to help the industry meet its sustainability goals and thrive in a circular economy.

Acronyms and Abbreviations

AFRA	Aircraft Fleet Recycling Association
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
APRA	Automotive Parts Remanufacturing Association
CE	Circular Economy
CLSC	Closed-loop Supply Chains
CM	Circularity Metrics
CMP	Circular Material Passport
CO2-eq	Cardon Dioxide Equivalent
DBMS	Database Management Systems
DDP	Digital Product Passport
DfRem	Design for Remanufacturing
DT	Digital Twin
DWT	Deadweight Tonnage
EMF	Ellen MacArthur Foundation
EOL	End-of-life
ERN	European Remanufacturing Network
EU	European Union
GHG	Green House Gases
GT	Gross Tonnage
HP	Horsepower
HSE	Health, Safety and Environment
I4.0	Industry 4.0
IACS	International Association of Classification Societies
IHM	Inventory of Hazardous Materials
IMO	International Maritime Organisation
IoT	Internet of Things
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Lifecycle Analysis

LDT	Light Displacement Tonnage
MARPOL	International Convention for the Prevention of Pollution from Ships
ML	Machine Learning
MAT	Maritime Asset Tracker
MP	Material Passport
NGO	Non-Governmental Organisation
NOx	Nitrogen Oxides
O&G	Oil and Gas
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PAMELA	Process for Advanced Management of End-of-Life Aircrafts
PCB	Polychlorinated Biphenyls
PSI	Pound per Square Inch
PSS	Product Service Systems
QR	Quick Response
RFID	Radio Frequency Identification
RPM	Revolutions Per Minute
RRR	Remanufacture, Reuse, Recycle
SOx	Sulphur Oxides
SQL	Structured Query Language
SRDM	Smart Recovery Decision Making
TBT	Tributyltin
ULCC	Ultra Large Crude Carriers
VLOC	Very Large Ore Carriers

1 Introduction

"A journey of a thousand miles begins with a single step."

-Lao Tzu

1.1 Chapter Overview

This chapter is a summary of the research conducted in this thesis and provides a background on the circular economy concept and maritime transport. It also comprises the aim and objectives of this PhD study, along with a brief summary of its structure.

1.2 General Perspectives on Circular Economy

The circular economy (CE) represents a transformative shift from the traditional linear economic model, which has long dominated industrial practices. The linear economy operates on a straightforward, yet unsustainable, paradigm: resources are extracted, used to produce goods, and discarded as waste at the end of their useful lives. This approach has led to significant environmental degradation, resource depletion, and increased greenhouse gas emissions, prompting calls for a more sustainable model (MacArthur, 2013; Mitchell & James, 2015; Preston, 2012). The circular economy addresses these challenges by proposing a systemic approach where the value of products, materials, and resources is maintained in the economy for as long as possible, minimising waste and reducing the need for new resource extraction (Geissdoerfer et al., 2020).

The core of the CE model lies in its emphasis on closing the loop of product lifecycles through greater resource efficiency, reuse, repair, remanufacturing, and recycling. This approach conserves resources and fosters innovation, as industries are encouraged to redesign products and processes to achieve circularity (Sassanelli et al., 2019; Stahel, 2010). CE principles have already led to significant advancements in sectors such as automotive and aeronautics, contributing to more sustainable industrial practices (Gunbeyaz, 2019; McKenna et al., 2012). However, the maritime industry presents a complex and somewhat fragmented picture regarding CE adoption, despite its critical role in the global economy.

Raw material scarcity is an escalating concern that will increasingly affect various industries in the near future, including shipbuilding and the broader maritime sector. The depletion of critical resources such as iron, steel, and copper poses substantial challenges to the sustainability and productivity of these industries. Steel, for instance, is not only fundamental for the construction of ships due to its superior strength and durability but is also a material that meets stringent quality standards essential for ensuring the safety and longevity of vessels (Pournara & Sakkas, 2021; Yan et al., 2013). Similarly, copper, a key component in maritime applications, is vital for numerous ship systems, including electrical wiring and anti-corrosion measures, which are crucial for maintaining the operational integrity of ships over time (Schmidt, 2019). However, the growing scarcity of these materials, driven by factors such as over-extraction, geopolitical tensions, and supply chain disruptions, presents significant risks to the maritime industry's ability to meet the increasing demand for new vessels and to maintain the existing fleet effectively.

The implications of raw material scarcity go beyond mere supply chain disruptions; they underscore the inherent vulnerabilities of industries that rely heavily on finite resources. The maritime sector, in particular, is highly dependent on a stable supply of raw materials for ship construction and for the production of advanced onboard equipment. Most of the raw materials needed for manufacturing high-tech maritime equipment in developed countries are imported. This dependency introduces additional risks, as political instability, trade disputes, and economic sanctions can aggravate the scarcity and drive-up market prices, making it more challenging to sustain production levels. Recent global crises, such as the 2020–2023 semiconductor shortage, which severely impacted the production of high-tech components across industries (Mohammad et al., 2022), and the 2022 European energy crisis, which disrupted energy supplies and led to significant economic ramifications (Emiliozzi et al., 2024), serve as stark reminders of the potential consequences of resource scarcity and the importance of developing more resilient and diversified supply chains.

The growing concern over the finite nature of Earth's resources has also spurred a broader recognition of the need for sustainable resource management. The concept of resource scarcity is now seen as a critical factor in assessing the long-term sustainability of industrial activities and their impact on the environment. As the global population rises, the pressure on natural resources intensifies, necessitating more efficient and responsible resource utilisation strategies (Desing et al., 2020; Gupta et al., 2023). The escalating competition for these limited resources, particularly in a globally interconnected economy, underscores the necessity of transitioning from a linear economy to a circular economy. This transition is essential for reducing the environmental impact of industrial activities while ensuring that valuable materials are retained within the economy for as long as possible (Guo & Guo, 2024; Hrytsiuk et al., 2023).

1.3 General Perspectives on the Maritime Industry

Maritime transport is the backbone of international trade, responsible for over 80% of global trade volume (UNCTAD, 2022b). The industry's importance cannot be overstated, as it enables the seamless movement of raw materials, finished goods, and other products across the globe, underpinning global supply chains. However, this critical sector also faces significant environmental and social challenges. Maritime activities contribute considerably to greenhouse gas (GHG) emissions, accounting for approximately 3% of global CO2 emissions (Lindstad et al., 2023), as well as 10-15% of anthropogenic sulphur (SOx) and nitrogen oxide (NOx) emissions (Bjerkan & Seter, 2019). Even though most of the emissions are generated during the ship operation stage, equipment manufacturing and shipbuilding stages also contribute to that.

Furthermore, even though lower carbon intensity is projected for the future, the industry’s emissions are expected to intensify unless sufficient measures are taken and current practices are improved (Smith et al., 2021). In addition, the industry is a significant source of air and water pollution, contributing to the degradation of marine ecosystems and the health of coastal communities (Gössling et al., 2021; Li et al., 2022). Safety concerns, particularly in shipbreaking yards in developing countries, add another layer of complexity to the industry's sustainability challenges.

The environmental impact of the maritime industry is projected to intensify if current practices persist. With trade volumes expected to triple by 2050, the sector faces the dual challenge of accommodating increased demand while reducing its environmental footprint (OECD, 2023). The maritime industry recently updated its decarbonisation goals, which call for at least a 70% GHG emission reduction by 2040 and net-zero emissions by or around 2050 (IMO, 2023). This highlights the pressing requirement for innovative solutions to harmonise the industry's economic significance with its environmental and social obligations. The circular economy offers a solution, providing a framework for the maritime industry to transition towards more sustainable practices.

In this context, the maritime industry's focus on decarbonising vessel operations, while crucial, must be complemented by a parallel emphasis on maximising raw material retention through circular economy principles. The adoption of circular economy practices represents a profound shift towards a sustainable and resilient industrial model that directly confronts the challenges of resource scarcity. By embracing circularity, the maritime industry can enhance its sustainability, reduce its reliance on finite resources, and mitigate the risks associated with resource depletion. This dual approach—integrating circular economy principles with decarbonisation efforts—will be critical for the long-term viability of the maritime sector and its ability to navigate the complex challenges posed by an increasingly resource-constrained world.

Despite the potential of CE to address these challenges, its adoption within the maritime sector has been slow and limited. The industry has mainly concentrated on the recycling phase of the circular economy, specifically on recycling steel from decommissioned ships (Fariya et al., 2019; Gunbeyaz et al., 2020). While ship recycling is widespread and does contribute to material recovery, it represents only the most basic level of circular economy practice. This narrow focus on recycling overlooks the broader opportunities presented by other CE principles, such as reuse, remanufacturing, and repurposing of high-value onboard components like diesel engines, electronics, and navigation systems (Okumus et al., 2022). If properly utilised, these components could extend their lifecycle far beyond current industry practices, thereby reducing the need for new production and the associated environmental impacts.

The implementation of CE principles in the maritime industry is challenging. The industry is characterised by a diverse range of stakeholders, including ship designers, builders, operators, and recyclers, each with different priorities and levels of awareness regarding circular economy concepts (Milios et al., 2019). This fragmentation has resulted in a lack of coordinated efforts to integrate CE practices throughout the ship lifecycle, from design and construction to operation and decommissioning. For example, while OEMs (original equipment manufacturers) are beginning to recognise the value of CE principles, many other stakeholders still equate the circular economy primarily with recycling, missing out on the higher-value opportunities that other CE strategies can offer (Okumus et al., 2023c).

Moreover, the ship recycling process poses significant barriers to the effective implementation of CE principles. The current practices in ship recycling yards, particularly in regions with less strict environmental and safety regulations, often reduce in the quality of materials and components recovered from ships. This degradation limits the potential for these materials to be reused or remanufactured, thereby diminishing the overall effectiveness of the circular economy in the maritime industry (Gilbert et al., 2017; Wahab et al., 2018). There is a pressing need to improve the processes and technologies used in ship recycling to better align with CE principles, ensuring that valuable materials and components are preserved and can be reintegrated into the economy.

The concept of circularity is central to the circular economy, emphasising the importance of designing products and processes that enable materials to be kept in use for as long as possible within a closed-loop system (Sassanelli et al., 2019). This approach requires fundamentally rethinking how products are designed, used, and disposed of. Within the maritime sector, this process could entail designing ships with modular components that facilitate easier replacement, repair, and remanufacture, ultimately prolonging their utility and decreasing the demand for new resources (Blomsma & Tennant, 2020). Additionally, adopting digital technologies such as the Internet of Things (IoT) and blockchain could enhance traceability and transparency in the supply chain, enabling more efficient circular economy practices (Wilts & Berg, 2018).

To successfully implement CE principles, industries must also develop advanced closed-loop supply chains, or reverse logistics systems, that can effectively manage the flow of materials and components through their extended lifecycles (Lopes de Sousa Jabbour et al., 2018). One of the significant challenges in establishing such systems in the maritime industry is the lack of information and coordination among stakeholders across the ship's lifecycle. This information gap often leads to inefficiencies in the reverse logistics process, reducing the potential benefits of CE practices. However, modern digital infrastructures, including information systems and technological solutions, have the potential to overcome these challenges by providing better visibility and control over the entire lifecycle of maritime assets.

Furthermore, the current circularity performance of the maritime stakeholders is unknown. Monitoring the progress and effectiveness of circular economy adoption in the maritime industry is crucial to ensure that the transition towards circularity is both successful and sustainable. This requires the development of industry-specific key performance indicators (KPIs) that can measure the impact of CE initiatives on various aspects of the industry, including environmental performance, economic viability, and social responsibility (Saidani et al., 2019). These indicators would provide valuable insights for practitioners, policymakers, and decision-makers, helping them to guide the industry towards a more circular and sustainable future.

The potential benefits of transitioning to a circular economy in the maritime industry are significant. By adopting advanced CE principles, the industry can not only reduce its environmental impact but also enhance its economic competitiveness. For example, research confirmed that remanufacturing substantially reduces in manufacturing energy consumption and emissions, along with considerable cost savings for various engine parts and components (Afrinaldi et al., 2017). The remanufacturing of maritime engines has been shown to significantly reduce material consumption and costs, offering a compelling economic incentive for the industry to embrace circularity (Koehler, 2021; Okumus et al., 2023c). Moreover, applying advanced CE principles can contribute to the maritime industry's progress towards its ambitious decarbonisation targets, thereby contributing to global efforts to combat climate change.

In conclusion, the maritime industry's transition to a circular economy is both a necessary and strategic move that promises to deliver significant environmental, economic, and social benefits. While the industry currently lags behind other sectors in adopting CE practices, the potential for improvement is considerable. By rethinking the design, construction, operation, and decommissioning of ships through the CE lens, the maritime sector can achieve greater resource efficiency, reduce its environmental footprint, and create new economic opportunities. Successfully implementing of CE principles will require coordinated efforts from all stakeholders, supported by advanced technologies, robust supply chain management, and comprehensive monitoring tools. Ultimately, the transition to a circular economy will be critical for ensuring the long-term sustainability and resilience of the maritime industry in an increasingly resource-constrained and environmentally conscious world. Therefore, this PhD research intends to accelerate the maritime industry's transition to circular economy principles by promoting material retention and improving the value extraction from assets at the end of their lifecycle.

1.4 Aim & Objectives

This PhD research aims to facilitate the maritime industry's shift towards circular economy principles, promoting material retention and enhancing the value extraction from assets at the end of their lifecycle. This aim will be achieved by fulfilling the following specific objectives:

- To conduct a literature review on CE within the maritime industry and analyse circular practices across various transportation sectors for comparative insights.
- To assess current circular practices, gain insights into the overall situation in the maritime industry, and identify barriers for maritime circularity.
- To map high-value and high-potential onboard equipment, identifying opportunities for implementing CE practices to enhance their lifecycle value.

- To identify technology and strategy solutions that could enhance maritime industry's circularity, while examining current practices amongst well-known manufacturers.
- To conduct a marine engine remanufacturing case study to demonstrate firsthand advantages of advanced circular practices, followed by a comparative cost-benefit analysis with a new engine.
- To investigate the relationship between CE and digitalisation, with a focus on asset tracking systems like material passports to propose solutions for integrating digital advancements into the conventional merchant fleet lacking smart features.
- To create a robust database design to fill the existing gap for the merchant fleet, showcasing the advantages of a passport system through a case study.
- To review existing CE indicators for other industries and develop tailored maritime circularity metrics to measure, monitor, and benchmark CE performances of key maritime stakeholder groups.
- Overall, to establish a framework for implementing circular economy principles in the maritime industry, promoting sustainable practices and resource efficiency while enhancing economic growth and competitiveness.

1.5 Structure of this Thesis

This section provides a concise overview of the structure and layout of this thesis. In the thesis, Chapter 1 is a general introduction to the research topic, where general perspectives regarding the CE and maritime industry are briefly explained and important elements such as current ship recycling activities, maritime decarbonisation goals, raw material scarcity, and closed-loop supply chains are mentioned. In Chapter 2, detailed information on the evolution of CE and its principles is given. A comprehensive literature review focusing on CE in the maritime industry has been carried out. Subsequently, the maritime industry has been compared with other transportation industries in terms of the adoption of advanced circular practices.

Chapter 2 lastly presented the research gaps identified by the literature review and the overarching research question. Overall methodology, and the positioning of this PhD study are given in Chapter 3. In Chapter 4, barriers and opportunities of the CE in the maritime domain were investigated in detail. A comprehensive stakeholder questionnaire was conducted to find out the current perceptions and practices of stakeholders in the maritime industry towards circular economy principles. Major barriers identified are presented, potential opportunities of a circular transition are articulated, and a maritime circularity framework is introduced. Chapter 5 focused on technology and strategy solutions for a circular maritime industry. After highlighting various solutions, Chapter 5 delved into current procedures from well-known maritime equipment manufacturers and then examined a case study on marine engine remanufacturing. Chapter 6 is concerned with the digital infrastructure required to implement advanced CE practices for greater volume. A tailored database structure is proposed as an enabler of circular transition to bridge the gap for the existing merchant fleet. Chapter 7 developed circularity metrics dedicated to the maritime industry to measure the circularity performances of nine key stakeholder groups. Chapter 8 discusses the achievement of research aims and objectives, the novel contribution to the field, and the general discussion. Chapter 9 outlines the conclusions and recommendations for future research.

1.6 Chapter Summary

This chapter has explained the background of the maritime industry and CE, and summarised this PhD study's approach to support the maritime sector’s circular transition.

2 Literature Review

2.1 Chapter Overview

This chapter aims to provide a comprehensive overview of the state-of-the-art literature on the CE and its application within the maritime industry. Its primary objectives are threefold: (1) to identify and synthesise key concepts, principles, and practices of CE; (2) to highlight the critical gaps in knowledge and practice specific to the maritime sector; and (3) to establish a robust foundation for the research questions and methodologies pursued in subsequent chapters of this thesis.

The literature review was conducted systematically to ensure a rigorous and transparent process. First, Scopus and Web of Science databases were used to identify relevant publications, including journal articles, conference papers, book chapters, and review papers. The search queries incorporated the CE concept and its application to maritime contexts, focusing on shipbuilding, ship recycling, and other lifecycle stages. The search was restricted to English-language publications and employed inclusion and exclusion criteria to filter irrelevant or duplicate records. This process resulted in a curated body of 50 key publications, which were then reviewed in depth to extract insights and identify gaps in knowledge.

The review process also followed a structured protocol for analysis. Definitions, frameworks, and principles of CE were mapped across industries to establish a baseline understanding. Then, comparisons were drawn to assess the maritime industry's current standing relative to other sectors such as automotive and aviation, which are more advanced in adopting CE practices. The review was augmented by visual tools, such as trend analysis of publication outputs, to contextualise the maritime industry's trajectory in adopting CE principles.

By synthesising findings from the literature, this chapter identifies significant gaps in knowledge related to the adoption of advanced circular practices in maritime operations. These gaps highlight the need for novel research contributions, such as empirical case studies, development of enabling technologies, and metrics tailored to the maritime industry. Through addressing these gaps, this chapter sets the stage for the overarching research question and the methodological framework that guides this thesis.

2.2 The Circular Economy (CE) Concept

The circular economy concept emerged as a response to the linear economy (Boulding, 1966; Pearce & Turner, 1990), which is wasteful and dangerous to the environment (Michelini et al., 2017). In the linear economy model, goods are produced from raw materials, sold to end-users, and sent to waste once the economic life ends (Jawahir & Bradley, 2016), also known as the take-make-use-destroy model (Ghisellini et al., 2016). One such solution to this phenomenon is the concept of the CE, a transformative economic framework aimed at reconfiguring production and consumption practices for sustainability (Lehmann et al., 2022). The CE approach focuses on reusing existing materials rather than using raw materials (Kok et al., 2013), reduces waste, and monitors resource consumption with the closed-loop approach (Govindan & Hasanagic, 2018).

Some of the most prominent and comprehensive definitions of CE in the literature are as follows:

- “an economic system in which resource input and waste, emission, and energy leakages are minimised by cycling, extending, intensifying, and dematerialising material and energy loops. This can be achieved through digitalisation, servitisation, sharing solutions, durable product design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling” (Geissdoerfer et al., 2020; Geissdoerfer et al., 2017).
- "an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals which impair reuse, and aims to the eliminate waste through superior design of materials, products, systems, and, within this, business models" (MacArthur, 2013).

- "an economic system that replaces the end-of-life concept with reducing, alternatively reusing, recycling, and recovering materials in production, distribution, and consumption processes" (Kirchherr et al., 2017).
- "In a CE, the resource loop would be closed so that large volumes of finite resources (metals and minerals, for example) are captured and reused" (Preston, 2012).

All these definitions indicate that CE is a crucial concept with substantial gains (Grafström & Aasma, 2021). It is vital for overcoming future resource scarcity and the environmental damage the current linear economy approach is causing (MacArthur, 2013; Mitchell & James, 2015; Preston, 2012). The CE approach focuses on improving the utilisation of resources, increased value retention, and extraction through reuse, repair, remanufacture, and recycling (Milios et al., 2019; Roos, 2014; Tukker, 2015). Resources recovered or retained through these activities minimise the use of raw materials, labour, energy, and capital and minimise the environmental impact caused during manufacturing operations. In addition to the benefits of resource preservation and environmental protection, the circular economy is also expected to create economic benefits of up to $1 trillion annually, with the manufacturing industry potentially benefiting by up to €600 billion (Grafström & Aasma, 2021; Kalmykova et al., 2018).

The realisation of closed-loop CE includes CE principles or strategies frequently referred to as R-imperatives, R-frameworks, or RE-terms. Various studies put forward different R frameworks. Initially, 3R (reduction, reuse, and recycling) principles were the dominant approach (Yuan et al., 2006), but increased awareness has added recovery, redesign, and remanufacturing to these principles, becoming the 6R (Gong et al., 2020; Govindan & Hasanagic, 2018). Some other studies and frameworks can be listed as 3R (Ghisellini et al., 2016; Kirchherr et al., 2017), 4R and 6R (Sihvonen & Ritola, 2015), 9R (Potting et al., 2017), and 10R (Reike et al., 2018). The CE literature comprises numerous alternative re-words in varying combinations in different studies. Reike et al. (2018) have listed them alphabetically as "re-assembly, recapture, reconditioning, recollect, recover, recreate, rectify, recycle, redesign, redistribute, reduce, re-envision, refit, refurbish, refuse, remarket, remanufacture, renovate, repair, replacement, reprocess, reproduce, repurpose, resale, resell, re-service, restoration, resynthesise, rethink, retrieve, retrofit, retrograde, return, reuse, reutilise, revenue, reverse, and revitalise". Such a variation is not surprising considering the wide spectrum of industries trying to achieve CE. However, this section aims to present the most impactful and widely-used frameworks. For that purpose, Figure 2-1 below presents the definitions of popular CE principles while Figure 2-2 illustrates one of the most famous CE diagrams out there to visualise the principles in an overall system.

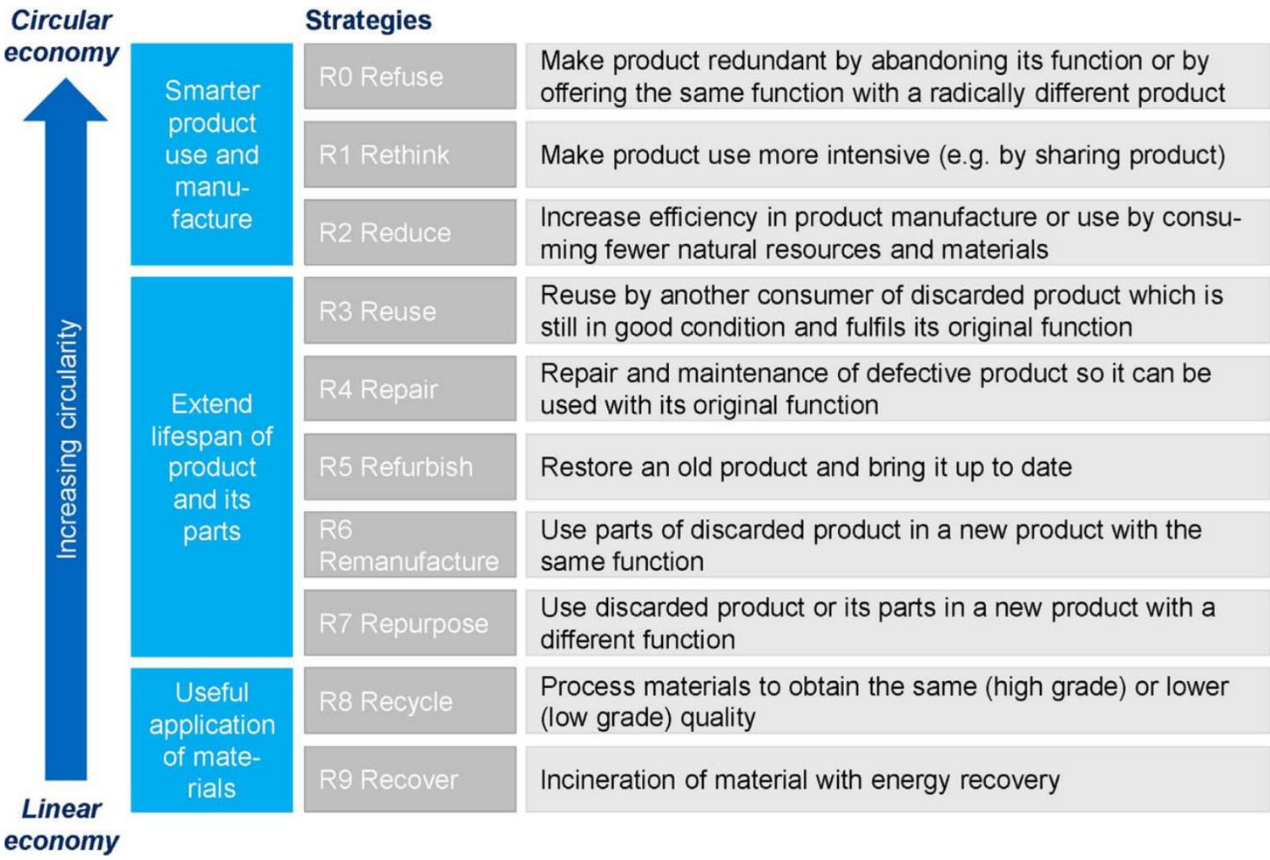

Figure 2-1: Circular economy principles in 9R framework, from (Kirchherr et al., 2017).

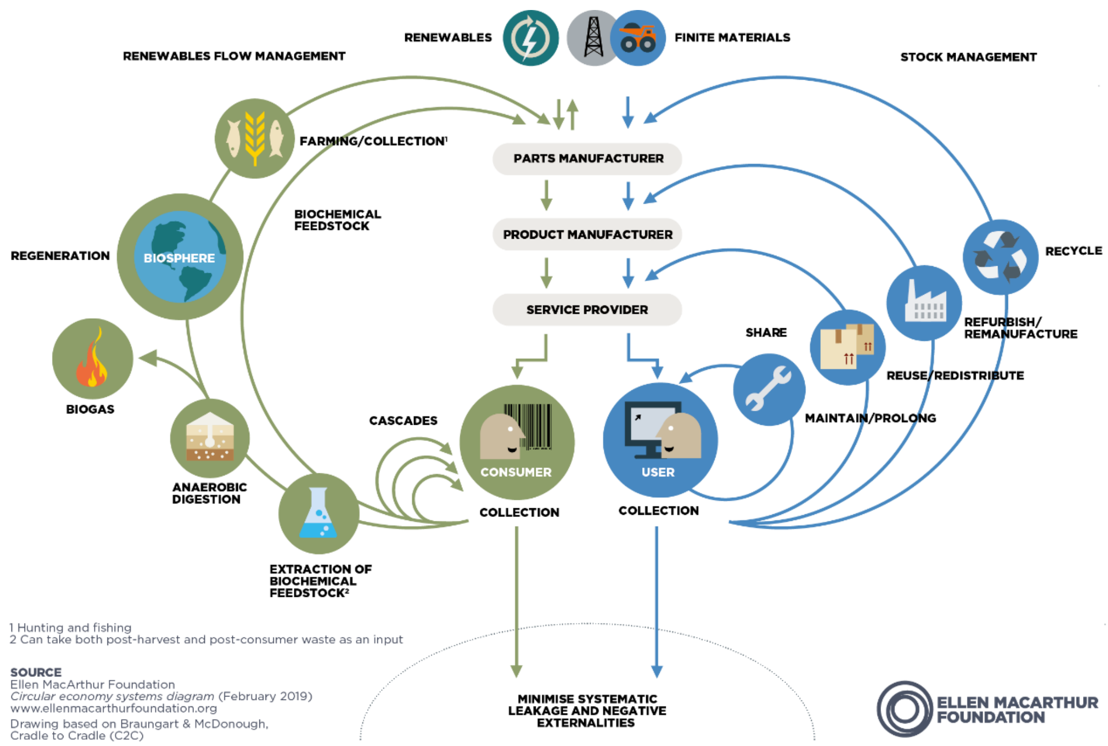

Figure 2-2: CE butterfly diagram showing biological and technological cycles, from (Ellen MacArthur Foundation, 2019).

The CE concept's evolution can be examined in three phases: CE 1.0, CE 2.0, and CE 3.0 (Razmjooei et al., 2024; Reike et al., 2018). CE 1.0, which covered a timeline between the 1970s and 1990s, mainly dealt with waste. The first lifecycle thinking concepts were introduced and contributed to system thinking in this phase (Gertsakis & Lewis, 2003), while the 3R concept of reduce, reuse, and recycle gained increased attention (Reike et al., 2018). During this time, a substantial amount of literature was centred around recycling and waste management. In CE 2.0, spanning the 1990s to 2010, the focus shifted towards integrating input and output strategies for eco-efficiency. This phase saw the emergence of concepts like industrial ecology and integrated life cycle thinking, emphasising a win-win scenario where environmental benefits align with economic gains. Businesses have started to recognise the advantages of proactive environmental strategies. Finally, CE 3.0, from 2010 onwards, combines older elements with a new emphasis on maximising value retention due to growing concerns about resource depletion. This phase highlights the urgency of decoupling economic growth from resource use, promoting a broader system perspective that includes diverse stakeholders such as consumers, NGOs, and governments. CE 3.0 aims to incorporate comprehensive value retention options, including remanufacturing, refurbishing, and repurposing, making it a more transformative approach towards sustainability (Reike et al., 2018). These concepts illustrate how reverse logistics and closed-loop supply chain management are closely related to CE (Razmjooei et al., 2024).

From a system analysis viewpoint, the transition to a circular economy can occur at nano, micro, meso, and macro levels. The CE at the nano-level is focused on products; the CE at the micro-level (industrial) focuses on companies or consumers (de Oliveira et al., 2021). The meso-level deals with industry-level systems such as eco-industrial parks or industrial symbiosis. The macro-level covers cities, regions, or nations (Kirchherr et al., 2017; Razmjooei et al., 2024). In all levels, CE principles aim to minimise waste, extend product life cycles, and optimise resource use by promoting CE practices such as recycling, remanufacturing, and sustainable design (Geissdoerfer et al., 2020; MacArthur, 2013). By closing the loop, CE reduces the need for new raw materials and mitigates the environmental impact of production and consumption (Neves & Marques, 2022).

While CE practices aim to reduce waste and extend product life cycles, some researchers caution that an increase in circularity levels may inadvertently lead to overconsumption. By making products more environmentally friendly or resource-efficient, consumers might be encouraged to purchase more, leading to a "rebound effect" where overall consumption rises despite the intended resource savings (Korhonen et al., 2018). Similarly, Jevon's paradox (Alcott, 2005) can be valid as circular products lead to reduced costs, which may encourage higher consumption rates, thereby limiting environmental benefits. This tension between circularity and sustainability is important to acknowledge, as higher levels of circularity do not automatically equate to greater sustainability (Ghisellini et al., 2016). Circularity focuses on closing resource loops and reusing materials, but without addressing consumption patterns and reducing the overall demand for products, CE can fall short of achieving true sustainability. Therefore, long-term sustainability requires a holistic approach that not only considers circularity but also tackles consumption behaviours. Upon reaching specific levels of circularity, it is essential to integrate sustainable consumption with circular production strategies to secure long-term environmental benefits instead of promoting overconsumption (Zink & Geyer, 2017). Managing this balance is crucial, particularly in industries with high resource use.

Reducing natural resource reserves and the environmental damage caused by globalisation and consumerism have increased interest in the CE concept. Research on the circular economy is constantly evolving (Sassanelli et al., 2019). There is a wide range of studies focusing on the circular economy approach in many different areas, such as textiles (Jia et al., 2020), manufacturing (Lieder & Rashid, 2016), construction (Smol et al., 2015), supply chains (Zhu et al., 2010), and services (Tukker, 2015). However, the literature on the circular economy approach to the maritime sector is quite limited (Milios et al., 2019; Okumus et al., 2023b). Section 2.3 will specifically investigate the situation in the maritime in a great detail.

2.3 CE in the Maritime Industry and Comparison with Other Industries

According to the latest June 2024 data, about 108,787 ships are sailing globally, with an average age of 22.4 years (UNCTADstat, 2024). Jansson (2016) reported that more than half of the fleet was over 15 years old in 2016, and recent reports show similar trends as 54.2% in 2023 (UNCTAD, 2023). These ships go through the lifecycle stages mentioned in the previous section: design, construction, operation, repair and maintenance, and end-of-life stages. Brief definitions of essential end-of-life concepts from a technical perspective are as follows:

Reuse: The European Commission’s Waste Framework Directive (EC Directive, 2008) defines reuse as “any operation by which products or components that are not waste, are used again for the same purpose of origin” (Milios et al., 2019).

Remanufacture: Lund refers to remanufacturing as reusing the product or component with properties equal to those of a new product after a remanufacturing process (Lund, 1984; Milios et al., 2019) with the possibility of technological upgrades if necessary (e.g., complying with a newer regulation) (Nasr & Thurston, 2006). As a critical CE strategy, remanufactured products offer a warranty equivalent to or better than the newly manufactured product (Jansson, 2016; Östlin, 2008).

Repair: Ship repair is defined as the "*overhaul, refurbishment, renovation, improvement, or alteration of the hull, machinery, equipment, outfits, and components of ships*" (MIA, 2018).

On the other hand, the terms **retrofitting or refitting** are more common terminologies in the maritime industry for overall vessels than remanufacturing or refurbishment, which are not usually associated with ships (Wahab et al., 2018).

Refit is described as repairing, fixing, and restoring an existing ship inside a shipyard to maintain the vessel's systems. It can include relatively minor changes or significant changes such as total overhauls or redesign of spaces. On the other hand, **retrofit** is the adaptation of the ships to the market, emission requirements or regulatory changes or necessities (RETROFIT, 2015).

Recycling is the demolition, decommissioning, dismantling or scrapping of the vessel at the end of its economic life to reacquire the materials – especially steel- onboard the ship. Recycling is the most common and environmentally (although contentious) safe option compared to shipwrecks, artificial reefs, or abandonment alternatives. As a result of the ship recycling operations, valuable material on board the ships, equipment, and machinery can be reobtained. In the old times, wood was reobtained, and nowadays, steel from vessels is precious. The potential of ship recycling in material recovery is vast, considering that 95–98% of ship materials by weight are recycled (Gunbeyaz, 2019; McKenna et al., 2012). As mentioned previously, most of a ship's weight consists of metals (ferrous and non-ferrous). Therefore, the high recycling percentage twists the situation and puts the industry in place rather than its actual condition. Moreover, the overall perception of the maritime sector in terms of circular economy is recycling, and the other aspects are mostly overlooked.

Recycling or reusing the materials is critical when an asset is at the end of its life, considering a potential future mineral scarcity (Henckens et al., 2014). In addition, producing steel from scrap requires around 1/5 to 1/3 of the production energy compared to hematite ore (Neşer et al., 2008; Sohn, 2020) and releases almost 1/10 of the carbon dioxide compared to production from the ore (SSI, 2021). Moreover, from a welding and construction perspective, Gilbert et al. (2017) demonstrated that a 50% hull reuse could provide a 10% emissions reduction in shipbuilding processes, and the emission reduction can be increased further to 29% less CO2 emissions if the entire hull is reused.

In theory, similar to other recycling industries, ship recycling can be considered an environment-friendly option and the closest part of the maritime industry to implementing the principles of circular economy. There are various valuable components on board commercial vessels. In particular, the engine room and bridge consist of main and auxiliary engines, hydraulic pumps and motors, compressors, navigation equipment, purifiers, electronics, computers, etc. Most of their components can be remanufactured, refurbished, or reused under the right circumstances rather than directly recycled. However, current practices in the industry prevent the full utilisation of the industry's potential, and do not promote more advanced CE strategies. As a result, the most common practice in the maritime industry is recycling, which is the lowest end-of-life hierarchy in a CE (Gilbert et al., 2017; MacArthur, 2013). It causes a reduction in quality and forfeits the remaining usable lifespan (Wahab et al., 2018) because most of the value-added labour and manufacturing energy are lost in the process (Okumus et al., 2023a). Figure 2-3 below illustrates maritime stakeholders and CE principles in the maritime industry.

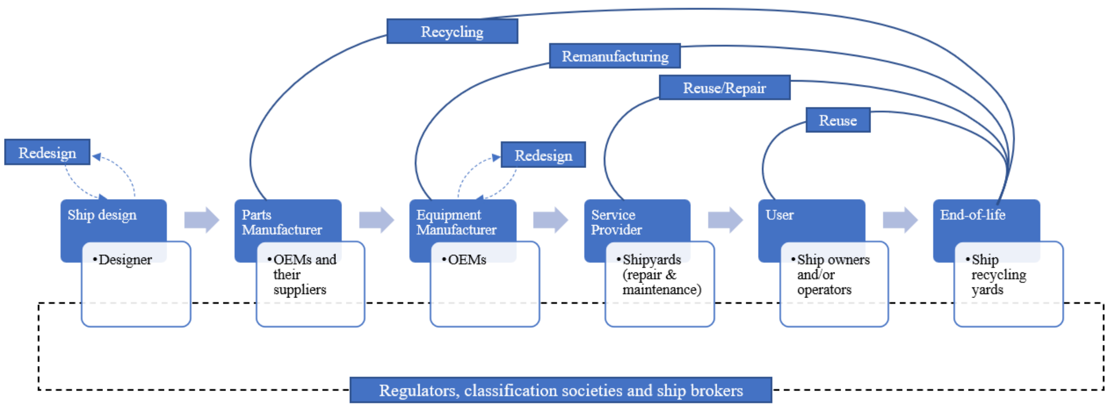

Figure 2-3: Maritime stakeholders and CE principles, from (Okumus et al., 2023b).

2.3.1 Approach to CE – State of the Art in the Maritime Industry

Following the Ellen MacArthur Foundation's leading efforts, the circular economy concept gained significant traction in 2013. This momentum was reflected in maritime literature in 2015, and a double-digit cumulative publication number was reached in 2018. Especially after 2021, the maritime circular economy literature has grown significantly, with a surge in research studies exploring various aspects of circular economy principles, as shown in Figure 2-4.

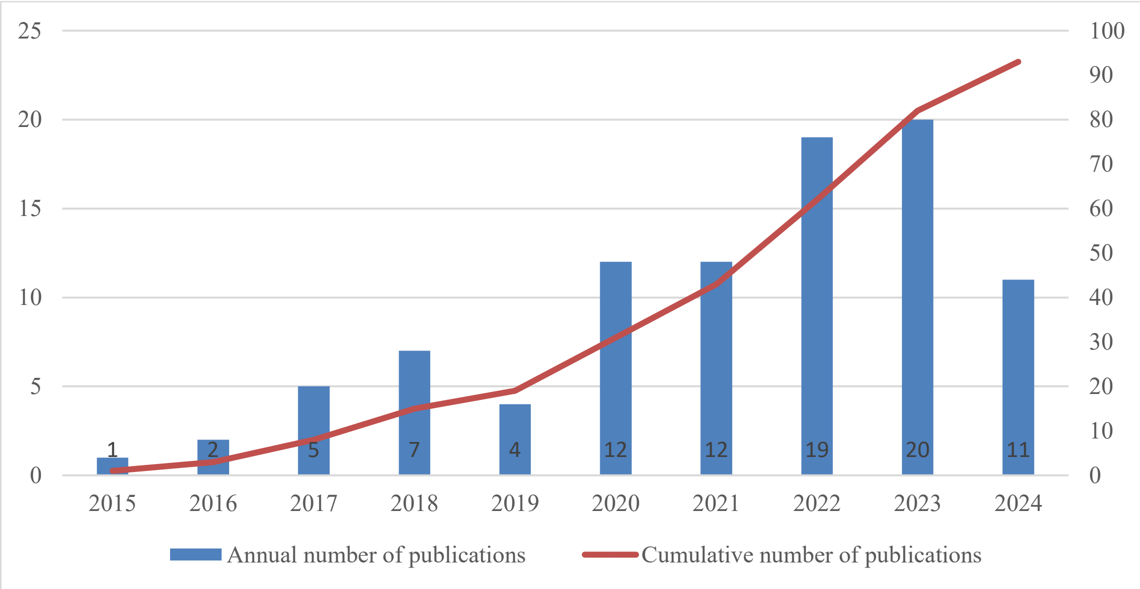

Figure 2-4: Number of unique publications obtained by literature search.

A comprehensive literature review was carried out within this chapter to capture the state of the art. The research protocol was developed by defining the inclusion and exclusion criteria illustrated in Table 2-1. The inclusion criteria included a wide range of publications: journal articles, review papers, conference papers, books, and book chapters; however, only publications written in English were included.

Table 2-1: Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Journal articles, review papers, conference papers, books and book chapters. Papers written in English and published in Scopus (83) and Web of Science (64).	Duplicates, full-text-missing publications, and papers focusing on irrelevant or specialised sectors (e.g., air freight, airships, home fabrication, chemicals, ocean litter, water treatment and agri-food waste).

The Scopus and Web of Science databases were employed for the search. Title, abstract, and keywords were included in the search, and the four queries below were used to cover the entire maritime industry, including a specific focus on shipbuilding and ship recycling operations. The asterisk wildcard was used to capture all spellings. The last search execution date is June 11, 2024.

Query 1: "circular economy" AND "maritime"

Query 2: "circular economy" AND "ship*build*"

Query 3: "circular economy" AND "ship*recycl*"

Query 4: "circular economy" AND "ship*break*"

These searches returned 147 publications in total. The first step of the filtering process in Table 2-2 excluded duplicates and full text missing publications. This has reduced the number to 93 publications. Then, their abstracts were read to check their alignment with this research. This step excluded 43 publications due to their extremely low relevance. These were publications focused on, for instance, water treatment, marine litter, air ships, waste plastics, and so on. The remaining 50 publications were fully read to capture their key findings and contributions to the field. Figure 2-5 shows the number of publications by year after final filtering.

Table 2-2: Publication filtering steps.

First filter	Second filter	Third filter
Duplicates, full-text-missing publications. (147 → 93)	Scan of abstract. Publications focusing on irrelevant or specialised sectors. Check that paper meets inclusion and exclusion criteria. (93 → 50)	Read of full paper (50).

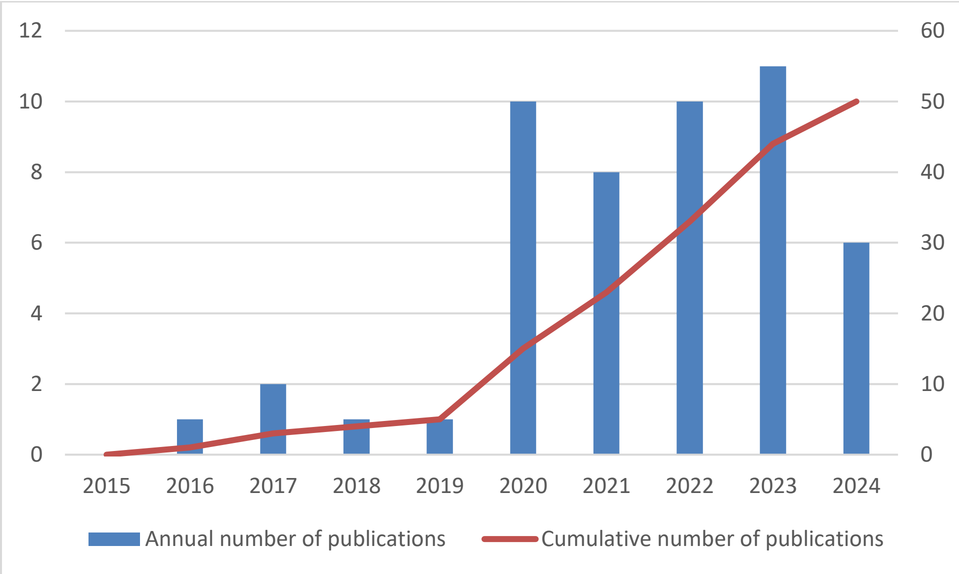

Figure 2-5: Number of publications after final filtering by years.

According to the literature review, the maritime industry is increasingly focuses on embracing CE principles to address sustainability and environmental impact challenges. Circular practices in the maritime sector involve strategies such as recycling, remanufacturing, recovery, and reduction (Razmjooei et al., 2024). These practices promote resource efficiency, reduce waste generation, and minimise the industry's carbon footprint.

Milios et al. (2019) have highlighted the adverse environmental effects and health and safety issues of widespread ship demolition practices, explored the conditions for increased reuse and remanufacturing practices in the Scandinavian maritime sector, stressing the significance of integrating CE practices to drive environmental sustainability and economic efficiency. However, Milios et al. (2019) primarily focus on a regional context (Sweden and Denmark) which limits the generalisability of their findings to the global maritime industry. Furthermore, while their study identifies the benefits of reuse and remanufacturing, it stops short of proposing actionable steps to implement these practices across diverse geographical and regulatory environments. This regional focus highlights a gap in the literature, as similar challenges may manifest differently in regions with less stringent regulations or different economic incentives.

Similarly, Tola et al. (2023) reviewed overall ship recycling operations and international efforts to support safe recycling, then identified CE as a potential leverage to enhance ship recycling practices in Europe. Implementing a circular economy model for ships involves strategic planning to address current and future challenges, particularly in ship eco-design, life cycle management, and recycling practices (Tola et al., 2023). Nevertheless, Tola et al.'s (2023) research primarily examines ship recycling within Europe and does not account for the complex variations in regulatory frameworks, technological capabilities, and economic conditions outside this region. Their analysis could benefit from a broader perspective that considers how CE principles might be applied globally, especially in countries where infrastructure for safe and efficient ship recycling is lacking.

Efforts to promote circular economy principles in the shipping industry are essential for enhancing sustainability and reducing environmental impact. Agarwala (2023) delves into promoting circular economy practices within the shipping industry, emphasising the need for concerted efforts to integrate circularity into the core operations of maritime businesses; furthermore, they discuss the material passport concept as a must to fully adopt CE in the maritime domain. While Agarwala's (2023) work highlights the importance of digital tools like material passports, this research lacks a comprehensive assessment of how such initiatives could be practically implemented and scaled industry-wide, particularly in regions where digital infrastructure and data-sharing standards are underdeveloped. This limitation reveals a gap in understanding how digital tools can be scaled effectively across different maritime contexts.

Circular shipbuilding practices are crucial in improving resource efficiency and reducing waste in the maritime sector (Scipioni et al., 2023). In their systematic review, Scipioni et al. (2023) identified reuse and remanufacturing as key strategies to close the supply chain in shipbuilding. However, their review focuses predominantly on new shipbuilding projects and offers limited insights on how these circular strategies might be applied to existing vessels. Given that a significant portion of the maritime industry's environmental impact comes from legacy fleets, further research is needed to adapt these principles to older vessels and end-of-life scenarios, which Scipioni et al.'s analysis does not adequately address.

Digitalisation has emerged as a key enabler of a maritime circular economy, with scholars emphasising its role in enhancing efficiency, transparency, and sustainability within the industry (Jensen et al., 2021). The concept of data-driven fleet monitoring is also being explored to enhance circular economy practices within the maritime industry. Oikonomou et al. (2021) pointed out that leveraging such advanced monitoring technology can optimise fleet operations and end-of-life strategies, improve fuel efficiency, minimise greenhouse gas emissions, and increase sustainability in the maritime sector. Although these studies underscore the benefits of digitalisation, they often treat it as a broad concept without providing specific frameworks that align digital tools directly with CE principles. Moreover, there is a lack of targeted research on how digitalisation can address unique challenges in the maritime sector, such as data standardisation across different stakeholder groups and the need for asset tracking systems throughout a vessel's lifecycle.

Additionally, life cycle assessments play a significant role in evaluating the environmental performance of ships and guiding decision-making processes during the early design stages. Gualeni and Maggioncalda (2018) introduced a lifecycle ship performance assessment framework that integrates cost and environmental aspects to inform decision-making in the early ship design stages. However, the effectiveness of these assessments is often constrained by data limitations and does not always account for the complexities of multi-stakeholder environments that characterise the maritime industry. While LCAs provide valuable insights, they are typically limited to new designs and fail to address challenges posed by legacy fleets. With further development, such key performance indicators could aid in the circular transition of the maritime sector by promoting keeping materials as long as possible in a cycle, encouraging maximum value extraction from the materials, and deciding the best end-of-life options for products.

Gilbert et al. (2017) discussed the role of material efficiency in reducing CO2 emissions during the ship manufacturing process, advocating for a life cycle approach to boost sustainability in the industry. This focus on material efficiency aligns perfectly with CE principles, which aim to minimise material waste and the multiple lifespans of products, hence improving resource utilisation. However, the study focuses primarily on the hull production phase, leaving out a critical analysis of how material efficiency can be enhanced through onboard equipment remanufacturing and recycling throughout the ship's lifecycle. By focusing narrowly on hull production, Gilbert et al. overlook the potential gains in extending material efficiency across the entire lifecycle of ships.

Steuer et al. (2021) investigated the potential of the CE principles in managing end-of-life ships, suggesting alternative approaches to handling ship disposal in a more sustainable manner. Remanufacturing has emerged as a significant aspect of extending the life cycle of marine products and structures, contributing to enhanced reliability and safety while supporting the circular economy within the maritime industry (Wahab et al., 2018). Similarly, Jansson (2016) emphasised that remanufacturing is a key strategy within the circular economy, enabling the reduction of CO2 emissions, saving materials, labour, and energy while prolonging the lifespan of products, components, and systems. Yet, none of these studies comprehensively evaluate how remanufacturing practices can be standardised or scaled across the maritime industry. This gap reveals a need for more research into the practicalities of remanufacturing within a diverse and complex industry like maritime, where stakeholders may have varying levels of awareness and readiness to adopt sustainable practices. Understanding the challenges and opportunities specific to the maritime sector is crucial for developing effective strategies to implement remanufacturing on a larger scale.

In summary, although existing research provides valuable insights into the potential of CE in the maritime industry, it often lacks comprehensive frameworks that account for diverse geographical, operational, and technological variations within the sector. These limitations highlight the need for further research to develop adaptable and scalable CE frameworks that can be effectively implemented across the global maritime industry. This thesis aims to address these gaps by proposing an integrated approach to circularity in maritime, incorporating tailored strategies, stakeholder-driven insights, and digital solutions to meet the unique demands of this industry.

2.3.2 Approach to CE – Current Practices in the Maritime Industry

Stakeholder considerations have also been emphasised in decision-making processes related to remanufacturing, underscoring the importance of engaging various stakeholders in promoting circular economy practices within the industry (Akano et al., 2021). Moreover, perspectives on the CE in different regions, such as Bangladesh, have been explored to understand the unique challenges and opportunities for implementing circular practices in ship recycling (Ahasan et al., 2021). Bangladesh is leading the ship recycling business with around 37.2% market share (UNCTAD, 2023). The research highlighted the importance of addressing capability and know-how gaps in ship recycling facilities, demonstrating potential financial gains, and developing a market and business model for circular products in the maritime industry (Ahasan et al., 2021). A former major ship recycling country, China, has significantly decreased its ship recycling volume due to the waste import ban and decreased scrap metal demand in the Chinese economy (MEE, 2018). However, China has an important market share and experience in shipbuilding and repair operations with significant industrial capacity. Steuer et al. (2021) discussed that Chinese ship recycling facilities could have adopted remanufacturing and other advanced CE principles if there was such a demand from the modern shipbuilding industry. This underlines the importance of alignment between industry stakeholders, as no stakeholder group alone could reach or implement circularity alone (Okumus et al., 2023c).

However, the momentum in the literature has not yet driven a corresponding increase in the operational implementation of circular economy principles in the maritime industry. In practice, ship recycling is one of the most hazardous jobs (ILO, 2004), involving a wide range of activities and operations that may expose workers to dangerous situations (OSHA, 2010) and harm the environment due to the toxic wastes on board ships and substandard procedures. As Kong et al. (2022) stated, the mainstream approach to ship recycling, commonly referred to as ship breaking, is distant recycling since regulations and policies vary from country to country. So in practice, end-of-life vessels were transported to less regulated countries for recycling in a dirty and dangerous way, which presents substantial environmental pollution and health threat risks to these regions (Hossain et al., 2016; Wan et al., 2016). Currently, most ship recycling occurs in developing countries: Bangladesh (37.2%), India (32.3%), Pakistan (16.9%), Turkey (6.3%), and China (2.4%) dismantle 95% of the total LDT (Devaux & Nicolaï, 2020; UNCTAD, 2023).

As the current capacity is mainly located in the abovementioned countries, there are additional challenges due to a lack of legislation, safety and environmental protection measures, and awareness. Local, national, and international stakeholders have severely criticised this, which eventually resulted in the development of the International Maritime Organization's (IMO) Hong Kong Convention (IMO, 2009) and the European Union's Ship Recycling Regulation (EC, 2016) as new regulations for the ship recycling industry.

Both regulations require ship recycling facilities to comply with the new standards, such as appropriate infrastructure, the establishment of procedures and techniques to minimise, reduce, and prevent hazards and risks, and systems to control any leakages. Although they are not perfect and are frequently criticised, both regulations require some changes and investments to be made in the ship recycling yards, improving the situation around them.

At the moment approach to the ship recycling yards is as follows:

- Ship recycling yards purchase the vessel (it might be directly from the last owner or a cash buyer). Following the necessary approvals from the local authorities, such as ministries or policymakers (for instance, the "No Object Certificate" from the Ministry of Industries in Bangladesh), the ship arrives at the ship recycling yard to be inspected for health and safety hazards. Following the inspection and cleaning, the cutting operation starts. Parallel to the cutting process, the workers remove equipment and machinery from the ship (Gunbeyaz, 2019).
- Different countries and ship recycling facilities each take a different approach at this stage. Some yards prefer removing the equipment themselves and selling it directly to potential customers. On the other hand, some yards prefer subcontracting this to third party sellers for removal and reselling. The removed equipment is usually separated and stored within the ship recycling yard area. However, these storage zones are unorganised, not tracked very well, and highly contaminated with various hazardous materials, including hydrocarbons, asbestos, and PCBs (polychlorinated biphenyls, e.g., caulk, paint, glues, etc.). Sample photographs from ship recycling facilities in Bangladesh, India and Turkey can be seen in the following figures:

Figure 2-6: Pictures from the yards in Chittagong, Bangladesh (Kurt & Gunbeyaz, 2020) .

Figure 2-7: Segregation and store zones in a Bangladeshi Ship Recycling yard in Chittagong (Kurt & Gunbeyaz, 2020).

Figure 2-8: Machinery waiting to be sold in the storage zone (Kurt & Gunbeyaz, 2020).

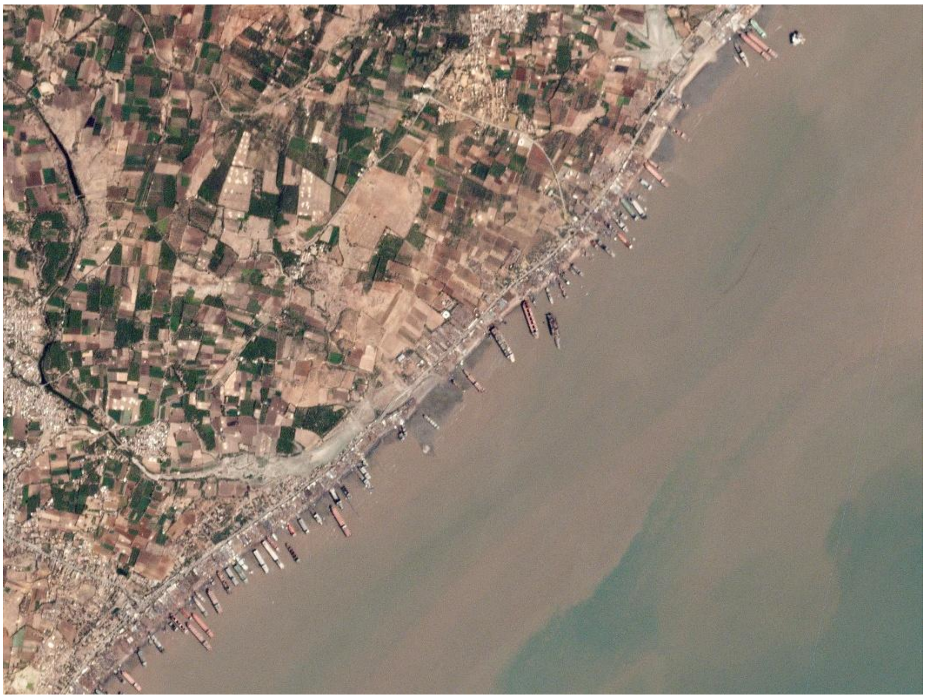

Figure 2-9: Alang shipbreaking yards in India, from ©Planet Labs PBC, CC BY-NC-SA 2.0 (2017).

Figure 2-10: Ship recycling yards in Aliaga region, Turkey from (Ship Recyclers' Association of Turkey, 2024)

Following removal from ships, equipment and machinery have three options:

- Recycled directly if the condition is poor or if there is no interest in the product from the used equipment market.
- Sold:
    - Sold for reuse directly (usually consumer goods – especially in the developing countries, some equipment are bought for home use rather than industrial applications).
    - Sold for pieces (some shipowners buy the equipment to be dismantled for parts if they have the same equipment)
- Reconditioned or Remanufactured: Although not common within the industry, some equipment is reconditioned and sold back to the consumer or buyer.

Especially in developing countries, third party shops that sell the items extracted from ship recycling yards are ubiquitous. The below pictures were taken in Chittagong, Bangladesh, and these stores serve the industry and the local community by selling these items.

Figure 2-11: "Second-hand shops" in Chittagong, Bangladesh (IMO-NORAD, 2015).

Figure 2-12: “Second-hand shops” in Chittagong, Bangladesh (IMO-NORAD, 2015).

Figure 2-13: "Second-hand shops" in Chittagong, Bangladesh (IMO-NORAD, 2015).

Figure 2-14: "Second-hand shops" in Chittagong, Bangladesh (IMO-NORAD, 2015).

Figure 2-15: "Second-hand shops" in Chittagong, Bangladesh (IMO-NORAD, 2015).

While the 6R (redesign, reduce, reuse, recycle, remanufacture, repair) concept has become more prevalent in other industries, including automotive and aeronautical transport modes, shipping presents a mixed overview (Gunbeyaz, 2019; McKenna et al., 2012). Ship recycling is a common practice in the maritime industry for end of life vessels (Gunbeyaz et al., 2020; Kurt et al., 2017), and it has long been viewed as the most environmentally friendly option when contrasted with the wasteful alternatives of sinking or abandoning vessels (Gunbeyaz et al., 2020; Kurt et al., 2017). Even though ship recycling contributes significantly to reducing the demand for emission-intensive mining of iron ore and new steel production through the utilisation of steel scrap, ship recycling remains a contentious issue. This is due to the poor working conditions in terms of health and safety and the damage caused to the environment as depicted from Figure 2-6 to Figure 2-15. Moreover, reuse and remanufacturing utilisation is very low compared to the other industries due to barriers in the maritime sector, which are explained in Section 4 of this thesis.

On the other hand, the materials used in the ship's hull, such as aluminium or steel, are degraded in terms of quality and usability further down in the lifecycle when recycled (Wahab et al., 2018). Even though recycling is not commonly considered of as the most favourable phase of the circular economy, maritime industries' approach to CE mainly focuses on recycling operations. It appears that there is a lack of understanding of the term 'circular economy', leading the sector to automatically emphasise the recycling stage when discussing CE principles. It is essential for the industry to prioritise alternative options like reuse, retrofitting, refurbishing, and remanufacturing. Currently, these options are mostly overlooked. These approaches extend the lifecycle of items and align with the principles of a circular economy, promoting material utilisation efficiency and labour and energy conservation. Furthermore, while the economic and environmental advantages surpass recycling, they are not widely recognised within the maritime sector. Shipping companies and shipyards are currently not engaging in the direct reuse of end-of-life equipment and components.

2.3.3 Application of Advanced CE Principles in Transportation Industries

Advanced CE principles include superior R-imperatives such as reuse, remanufacturing, refurbishing, and repurposing. Although various studies and resources define these principles slightly differently, in the literature, reuse and remanufacturing are more commonly used. In the circular economy framework, the relationship between remanufacturing and reuse is interconnected and complementary. While remanufacturing involves refurbishing products to a high standard, reuse emphasises the direct utilisation of products or materials in their existing state, thereby promoting resource efficiency and waste reduction. Both practices contribute to the CE's goal of circulating products, components, and materials for as long as possible, while remanufacturing mainly involves reusing some parts and components and reconditioning others (Aleksić et al., 2022).

CE promotes closed-loop recycling systems where the material returns to the original, same product system (Karvonen et al., 2015). Therefore, remanufacturing requires a reverse logistics structure to complete the material cycle. Remanufacturing can be defined as a system that consists of external and internal processes (Jansson, 2016). Figure 2-16 below depicts how a remanufacturing system functions during the circularity journey. The external process corresponds to the acquiring the core components and selling the remanufactured (often called "reman") products (Karvonen et al., 2015). In contrast, the internal process corresponds to the operation of remanufacturing itself. In this notation, the reverse supply chain part covers the flow of goods from customers and forms the "restorative closed-loop supply chain. Therefore, this section will compare the application of advanced CE principles in the automotive, aviation, and maritime industries by mainly focusing on remanufacturing.

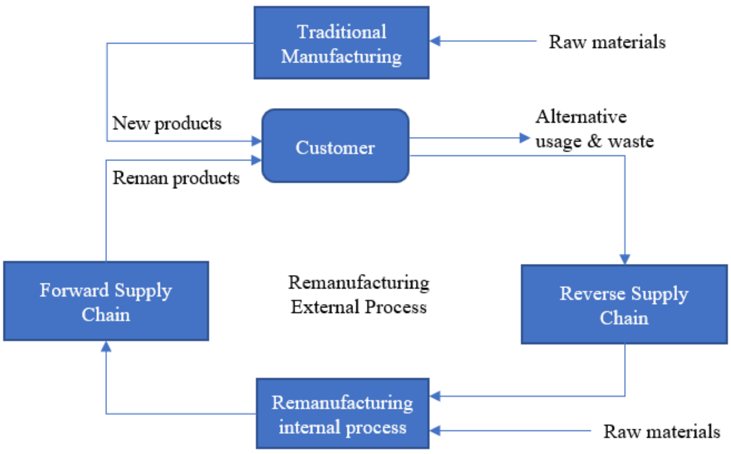

Figure 2-16: Forward and reverse supply chains in remanufacturing, from (Okumus et al., 2023b)

Currently, the total remanufacturing industry provides approximately 180,000 jobs in the US and more than 450,000 jobs worldwide (RIC, 2024). On the other hand, the European market is currently just under €30 billion and employs around 190,000 people. However, recent European market studies estimate the industry volume to reach €90 billion by 2030 and employ around 255,000 people (Circle Economy, 2024; CRR, n.d.; ERN, n.d.). Table 2-3 below summarises the current remanufacturing activities across various industry sectors in Europe. As clearly indicated in the table, the aviation and automotive industries are leading, while the maritime industry lags behind heavily (Totaro, 2021).

Table 2-3: Summary of European Remanufacturing activities across industry sectors, modified from Jansson (2016).

Sectors	**Turnover (€bn)**	**Firms**	**Employment ('000)**	**Cores ('000)**	**Intensity**
Aerospace	12.4	1,000	71	5,160	11.5%
Automotive	7.4	2,363	43	27,286	1.1%
EEE	3.1	2,502	28	87,925	1.1%
Furniture	0.3	147	4	2,173	0.4%
	4.1	581	31	7,390	2.9%
Machinery	1.0	513	6	1,010	0.7%
Marine	**0.1**	**7**	**1**	**83**	**0.3%**
Medical Equipment	1.0	60	7	1,005	2.8%
Rail	0.3	30	3	374	1.1%

Remanufacturing efforts in the aviation industry

In the aviation and aerospace industries, the overall design life of an aircraft is typically 20 to 30 years (DAC, 2019). On the other hand, the average service life of aircraft is declining, with planes 15 years old or newer increasingly being scrapped (Jensen & Remmen, 2017; Keivanpour et al., 2013). In the next 20 years, an estimated 8,500 to 12,500 planes are expected to reach their end of life (DAC, 2019; Jensen & Remmen, 2017; Van Heerden & Curran, 2011). Consequently, many aviation companies have initiated programmes to address this challenge effectively.

The Aircraft Fleet Recycling Association (AFRA), founded in 2005 by Boeing and ten founding partners, *"promotes environmental best practices, regulatory excellence, and sustainable developments in aircraft disassembly, salvaging, and recycling parts and materials"* (AFRA, 2022). Since its launch, AFRA has dismantled more than 9,000 aircraft and grown to include over 40 members, ranging from OEMs to recyclers, from insurers to technology developers (AFRA, 2022; DAC, 2019). Alongside AFRA, Airbus launched the PAMELA (Process for Advanced Management of End-of-Life Aircrafts) project in 2005, which demonstrated the feasibility of recycling plane components up to 85% and emphasised the importance of material mapping in the design phase to support high-value recycling at the end of an aircraft's life (Airbus, 2008; Jensen & Remmen, 2017). The impacts of such multi-stakeholder global associations are reflected in the aerospace industry's leading performance of €12.4 billion turnover, 71,000 employment, and more than 5.1 million cores remanufactured, as presented in Table 2-3.

The remanufacturing process within the aviation industry often involves critical aircraft modules such as engines, avionics and landing gear which typically undergo remanufacturing at least once during their lifecycle (Wahab et al., 2018). In this context, remanufacturing is crucial for ensuring safety and compliance, given the strict regulations and the need for certified procedures by qualified personnel (Keivanpour et al., 2015).

Hashemi et al. (2016) developed a mathematical model that accounted for varying remanufacturing lead times and defect rates of core components. Their study aimed to optimise a closed-loop material cycle in the aerospace sector by focusing on the remanufacturing of customer-owned products and components. The results highlighted a significant reduction in waste and scrap metal, along with increased profits due to reduced costs associated with new material procurement and waste disposal. This research underlines the tangible benefits of remanufacturing in terms of environmental impact reduction and profitability enhancement. This is particularly relevant in industries where the cost of materials is high and manufacturing processes are complex.

Building on these findings, Hyvärinen et al. (2023) explored closed-loop recycling and remanufacturing of polymeric aircraft parts. They developed a prototype part to demonstrate the viability of closed-loop recycling by successfully remanufacturing it. The study provides a comprehensive look at the possibilities and challenges of integrating closed-loop recycling within the aviation industry, suggesting that with further development and economic validation, this approach could represent a viable path towards more sustainable manufacturing practices.

According to Jensen and Remmen (2017) a significant challenge within the aircraft industry is the absence of specific directives, coupled with the complexity of the designs and stakeholder relationships. This issue mirrors similar challenges faced in the maritime industry, indicating a broader pattern of complexity in remanufacturing practices across different sectors.

Remanufacturing efforts in the automotive industry

Automobile parts remanufacturing represents the largest remanufacturing industry globally (Wahab et al., 2018), with the global remanufacturing market in the automotive sector valued at 60.78 billion US dollars in 2022. It is projected to grow to 126 billion US dollars by 2030 (Fortune Business Insights, 2024). Remanufacturing in the automotive sector involves a standardised industrial procedure where worn-out, previously owned, or inoperative automotive parts are restored, reconditioned, rebuilt, and transformed into brand-new parts through processes including cleaning, disassembly, repair, and replacement of worn or obsolete components.

The main drive of the remanufacturing market is the anticipated demand for replacing end-of-life components or worn-out parts. Leading OEMs such as Bosch, ZF Friedrichshafen AG, and others focus on this growing remanufacturing market, offering remanufactured products that are both economical and comparable to brand-new alternatives (Fortune Business Insights, 2024).

While average product size and costs are much smaller in the automotive industry compared to other sectors, the CE principles are more readily implemented here. Automotive remanufacturing is predominantly represented by the Automotive Parts Remanufacturing Association (APRA), established in 1941 and now has 2,000 members globally (APRA, 2021). APRA champions remanufacturing as an integral part of the circular economy and advocates for the interests of the industry, which include free trade, an independent aftermarket, and legal certainty. This association emphasises the need for remanufacturing to be actively promoted by relevant stakeholders, such as politicians, authorities, and companies.

The average lifetime of vehicles in the EU is 10–12 years, which is lower than other transport industries. However, there are similarities between the products in terms of some subcomponents they possess; for example, all of the products have some kind of propulsion system involving engines as well as having a fundamental structure (car chassis and bodywork, ship hull, or aircraft bodies). In 2019, 6.1 million passenger cars, vans, and other light goods vehicles were scrapped in the EU, totalling 6.9 million tonnes; 95.1% of the recovered parts and materials were reused, which means that 89.6% of the recycled materials were reused (EUROSTAT, 2021).

Remanufacturing automotive subassemblies, such as brake systems, steering components, and suspension parts, is a common. This involves disassembly, cleaning, repairing, replacing worn parts, reassembly, and testing to ensure they meet performance specifications. Remanufactured subassemblies provide a cost-effective solution for vehicle maintenance and repair, allowing for the reuse of valuable components and reducing the environmental impact of automotive operations (Merkisz-Guranowska, 2017).

Moreover, the remanufacturing of automotive electronics, including control modules, sensors, and infotainment systems, is gaining importance. This process involves refurbishing and reprogramming these parts to restore their functionality and compatibility with modern vehicle systems. Remanufactured automotive electronics offer sustainable solutions for repairing and upgrading vehicle electronics, providing cost savings and reducing electronic waste in the automotive sector (Siddiqi et al., 2019).

Authorities and the public significantly influence the automotive industry through regulations, limitations, rules, and purchasing preferences, much like in other transportation industries but with notable contrasts, such as in the maritime industry. The EU's Directive on End-of-Life Vehicles (Directive, 2000) has pressured manufacturers to green their processes and supply chains, compelling suppliers to reuse, recycle, and adopt other forms of recovery for end-of-life vehicles and their components (Masoumi et al., 2019). Figure 2-17 below demonstrates the industry's benefit regarding recycled production vs. virgin production of essential raw materials. Consequently, remanufacturing has been reported to lower energy consumption by as much as 80% compared to manufacturing new parts, requiring 88% less water and releasing about 90% fewer chemicals. This approach can reduce waste by 70% (Rommel, 2018).

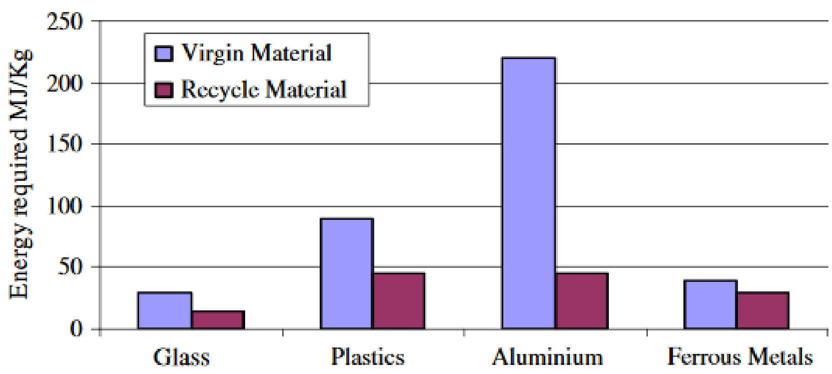

Figure 2-17: Energy required for the basic production of materials in the automotive industry (per kg) **(Masoumi et al., 2019; Weiss et al., 2000).**

Furthermore, Koehler (2021) showed that remanufacturing could save up from 5% to 52% of CO2-eq emissions while consuming 29 to 90% less material and 21 to 55% less manufacturing energy within the automotive industry, as illustrated in Figure 2-18.

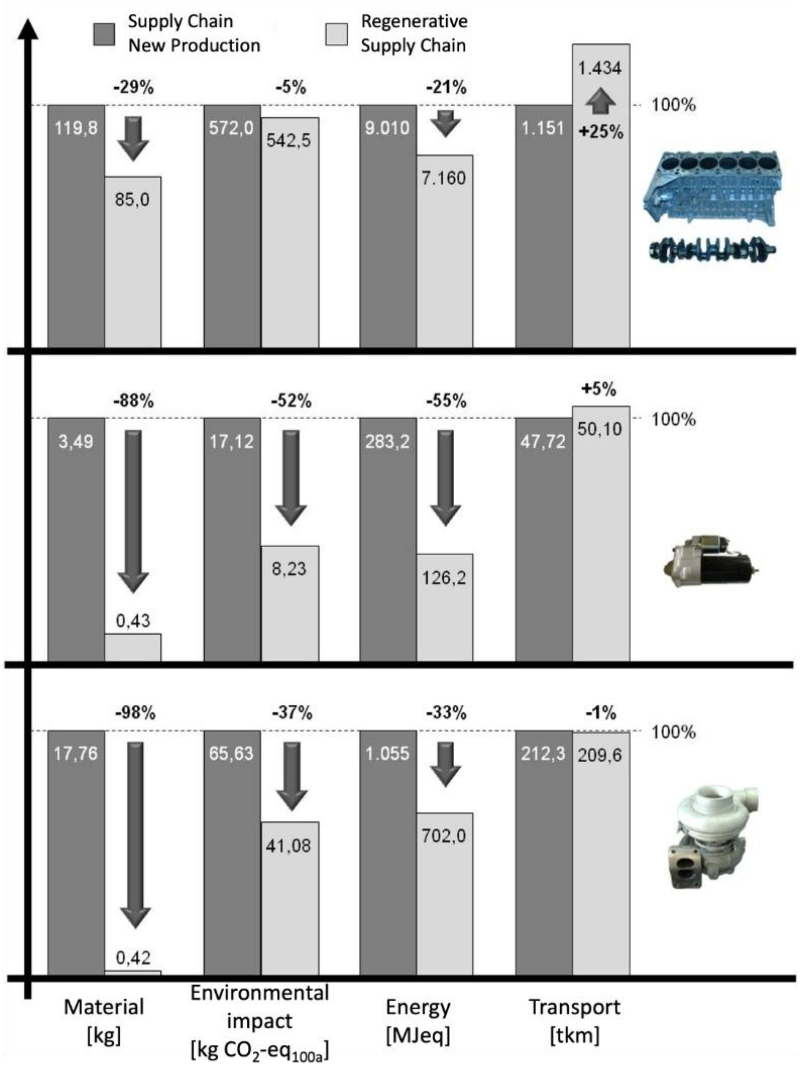

Figure 2-18: Energy, material, emissions and transport savings in remanufacturing (vs new product) of automotive parts (engine, starter and turbocharger) (Koehler, 2021).

According to a previous study by Smith and Keoleian (2004), complete engine remanufacturing resulted in a 65% to 88% reduction in solid waste generation and significant reductions in manufacturing emissions: CO from 48% to 88%, NOx from 72% to 85%, and SOx from 71% to 84%. On top of that, Zhang et al. (2021) demonstrated that remanufacturing significantly outperforms advanced recycling systems by preventing material degradation and maintaining the utilisation of valuable metals in automotive engines (43 years versus 18 years).

Overall, both the aviation and automotive industries have formed global associations to create awareness, share best practices, and ultimately increase advanced CE principles or R-imperative adoption rates on the path to sustainability. And in collaboration with those associations, practical research and case studies have been conducted to showcase the benefits of implementing advanced CE principles in both industries. These efforts have led to a greater understanding of the potential economic and environmental advantages of sustainable practices in aviation and automotive manufacturing. These examples clearly show the importance of cooperation and joint efforts among stakeholders worldwide to achieve a more sustainable industry.

Remanufacturing efforts in the maritime industry

The maritime industry is one of the industries that has yet to reach its remanufacturing potential. Reuse and remanufacturing are uncommon in the maritime sector, unlike other transportation industries such as aviation and automotive (Milios et al., 2019). Research by Milios et al. (2019) indicates that reuse and remanufacturing are uncommon in the maritime industry, primarily due to high costs that prohibit the uptake of reused and remanufactured components, a lacking and inconsistent policy framework, and the absence of organisational competencies to facilitate reuse. This is in utter contrast to the proactive remanufacturing practices observed in the automotive and aviation sectors.

The maritime industry's approach is significantly influenced by the potential for high penalties or substantial loss of profits due to delays. Shipyards, for instance, often refrain from reusing or remanufacturing equipment to prevent legal complications during new build, refit, or retrofit operations. Similarly, the offshore oil and gas (O&G) industry is hesitant about remanufacturing, as highlighted during discussions with industry stakeholders: "*Yes, we can install a remanufactured pump on the O&G line to save around £25,000. However, if the pump is broken, the hourly loss on the line is £100k, which I will not be able to explain to the customer.*" This anecdote clearly conveys the prevailing risk-averse mindset in the sector. A similar conclusion is also mentioned by Milios et al. (2019) for the shipbuilding and operation aspects of the maritime industry. The barriers to advancing CE in the maritime industry are further investigated separately in Section 4 of this thesis.

Despite these challenges, there are numerous opportunities for product recovery in the maritime sector. For instance, during dry-docking and overhauling, there is a heightened potential to exchange old equipment with remanufactured ones (Joensuu et al., 2023). Some equipment suppliers, especially engine manufacturers, lead remanufacturing efforts for valuable onboard components, including gas and diesel engines, transmissions, turbochargers, propeller shafts, and stern drives (Okumus et al., 2023c; Wahab et al., 2018). However, remanufacturing activities in the maritime industry lag significantly behind those in other transportation sectors, as previously outlined in Tables 2–5. According to the European Remanufacturing Network (ERN), the maritime industry's remanufacturing scale is extremely low compared to other transport modes, generating only €0.1 billion in revenue and employing 1,000 workers to handle 83,000 cores, in stark contrast to the automotive remanufacturing industry's €7.4 billion, 43,000 workers, and 27,286,000 cores (Parker et al., 2015; Wahab et al., 2018).

Despite the low remanufacturing rates (0.3% intensity), the maritime sector does see considerable savings in materials and CO2 emissions through remanufacturing efforts. Marine remanufacturing companies have managed to save up to 15,000 metric tonnes of materials and reduce CO2 emissions by 40,000 metric tonnes (Parker et al., 2015). Despite the current numbers showing a smaller scale of remanufacturing within the maritime sector compared to other industries, there is huge potential for growth. With significant savings in materials and CO2 emissions already being realised, expanding remanufacturing efforts in the maritime industry has the opportunity to make a substantial impact. By increasing remanufacturing rates and investment in this sector, the benefits could be even more significant in terms of revenue generation, job creation, and environmental sustainability. Moreover, the remanufacturing process involves rigorous inspection, testing, and quality control (Errington & Childe, 2013), resulting in products that are at least as reliable or more so than new ones (Brent & Steinhilper, 2004; Wahab et al., 2018). It is frequently stated that remanufactured products can offer equal or superior quality compared to new alternatives, along with appropriate warranty coverage (Fofou et al., 2021; IRP, 2018; King et al., 2006).

Ship or offshore platform remanufacturing does not happen on the scale of an entire vessel or platform, but occurs more in components, sections, or units. Although the current situation is not bright in the maritime industry, component-level remanufacturing is also causing some misinterpretations. For example, OEMs, such as engine manufacturers, can identify as machinery suppliers to multiple industries. Therefore their statistics may "leak" to other sectors rather than the maritime industry (Jansson, 2016). Moreover, the regulatory barriers within the industry prevent the direct use of remanufactured items. However, the only exception to this we see in practice is storing disassembled components as spare parts for the same vessel or her "sisterships" (a ship of the same class or design series as another ship) (Okumus et al., 2022).

As part of the life cycle, ship repair is an essential part of the industry but is often overlooked by circular economy researchers (Gunbeyaz, 2019; Jansson, 2016). However, the ship repair industry has several opportunities for remanufacturing. Jansson (2016) studied the ship repair activities in small-scale and large-scale ship repair to identify the potential of remanufacturing at this stage. Cores could be collected from the ship or shipyard during the repair activities and then sent to a suitable company for remanufacturing or reconditioning. The resulting product can be reused in other ships, shipyards, or even other industries. Table 2-4 below summarises the lifecycle activities and potential remanufacturing opportunities in ship repair processes and Table 2-5 provides several examples from the industry.

Table 2-4: Remanufacturing opportunities in ship repairing business (Jansson, 2016).

Lifecycle milestone	**Reman opportunity**	**Role of ship**	**Role of repair yard**
Maintenance	Yes	Core supplier	n/a
Small-scale voyage repairs	Yes	Core supplier	n/a
On-board repair	Yes	Core supplier	n/a
Planned dry-docking, ship overhaul	Yes	Customers of reman parts	The core collection, prepare 2nd life

Lifecycle milestone	Reman opportunity	Role of ship	Role of repair yard
Large-scale retrofit & refurbishments	Yes	Customers of reman parts	Remanufacturer
Modernisation	Minor	Core supplier	Core collector
Conversion, transformation	Minor	Core supplier	Core collector
Emergency & damage repair	n/a	n/a	n/a

Table 2-5: Remanufacturing in repair (Jansson, 2016).

Activity	Example
Small scale repair activity	breakdown maintenance, spare parts and component replacement, HVAC system maintenance
Dry dockings and overhauls	Diesel engine manufacturing – replacing cylinder covers, pistons etc.
Large scale repair and refurbishments	Cabin refurbishment, bathroom furniture and fittings, HVAC, piping etc
Ship conversions	modernisation, extending the ship's commercial life by approx. 20 years and conversion, lengthening, transformation to other usages

Even though it is unorganised and has many issues and difficulties, there is a significant potential for remanufacturing in the ship repair phase. Ship repair is a critical part of the life cycle and essential to keeping ships economically viable and safe for crew, environment, and goods carried. Implementing reuse and remanufacturing strategies in the maritime industry can extend the lifecycle of marine assets, thereby postponing the recycling stage and contributing to energy savings, resource efficiency, and reductions in costs and emissions. This approach not only aligns with efforts towards decarbonisation but also enhances the value of products through extended lifecycles and corporate social responsibility appeals to shipowners (Stahel, 2013).

Moreover, remanufacturing operations are advantageous for OEMs and independent remanufacturers as they provide skilled employment opportunities and contribute to economic growth in the surrounding communities (Karvonen et al., 2015; Koehler, 2021; Linder & Williander, 2017). Additionally, direct labour costs are significantly lower in the remanufacturing phase, as the tasks' complexity and manual require skilled human operators, unlike in new production, where material, equipment, infrastructure, and overhead costs dominate (Koehler, 2021).

In conclusion, while the maritime industry faces many challenges and currently needs to catch up in remanufacturing practices compared to the automotive and aviation industries, it holds substantial potential for growth in this area. Efforts to enhance remanufacturing could lead to significant environmental benefits and cost savings, mirroring the positive impacts seen in other transportation sectors.

2.4 Research Gap

The literature on CE in the maritime industry highlights several important initiatives; however, there remain significant gaps in knowledge that hinder the comprehensive adoption of advanced circular practices specific to maritime assets and stakeholders. Although the CE concept has gained traction in other transportation sectors, such as automotive and aviation, the maritime sector continues to lag, particularly in implementing practices beyond the basic recycling. While recycling in shipbreaking yards is common, it remains unclear how more resource-efficient and impactful practices such as reuse, remanufacturing, and refurbishing can be systematically integrated into maritime operations.

Below are the gaps in knowledge identified from the literature, which this thesis seeks to address:

- **What are the real-world benefits and feasibility of advanced circular economy practices for the maritime sector?**

  While the theoretical advantages of circular economy strategies such as remanufacturing, refurbishing, and reuse are documented, the literature lacks empirical studies that validate these benefits in a maritime context. The predominant focus on recycling in shipbreaking yards has left a gap in understanding how more advanced practices can be applied effectively to maritime vessels, systems, and components. How can case studies be designed to illustrate the operational, financial, and environmental benefits of these practices? This remains a significant area where practical evidence is missing, and research is needed to provide concrete examples that can guide stakeholders in adopting these advanced practices.

- **What specific enablers are required for the circular transition in the maritime industry?**

  Unlike other transportation industries such as aviation or automotive, the maritime sector faces unique challenges, including regulatory, operational, and logistical barriers that hinder CE adoption. What are the key enablers—such as reverse logistics, remanufacturing infrastructure, or policy frameworks—that can facilitate this transition? Although the literature highlights some enabling factors, the interdependencies between strategy, technology solutions, digitalisation, and stakeholder alignment remain underexplored. Future research should investigate these enablers in detail, focusing on practical implementation and their impact on accelerating the circular transition..

- **How can circular economy principles be extended to ageing merchant vessels?**

  While significant attention is given to newly built ships, the literature does not adequately address the inclusion of older ships in circular practices. What strategies or infrastructures are needed to retrofit ageing vessels and prevent underutilised assets from being prematurely discarded at the end-of-life stage? Further research is required to explore scalable solutions for incorporating these vessels into the circular economy, including retrofitting, remanufacturing, and lifecycle management. Additionally, how can these solutions be applied at scale, and what would be the financial and environmental impacts of such initiatives on the global fleet?.

- **How can the circularity performance of maritime stakeholders be measured and tracked effectively?**

  The maritime industry lacks specific frameworks or tools for evaluating circularity performance. What methodologies or indicators can be developed to provide consistent and actionable assessments of circular practices in the sector? While other industries have advanced in defining performance indicators for circularity, the absence of maritime-specific metrics creates a knowledge gap in how to measure and compare progress effectively. Developing tailored metrics, key performance indicators (KPIs), or assessment tools for maritime stakeholders is essential to establish benchmarks and encourage continuous improvement.

In summary, although progress has been made in exploring CE principles, these gaps in knowledge highlight critical areas that must be addressed to facilitate a comprehensive circular transition in the maritime industry. This thesis seeks to contribute to filling these gaps by providing new insights, practical solutions, and empirical evidence to advance the adoption of CE practices across maritime operations.

2.5 Research Question

The literature reveals critical gaps in the knowledge necessary for transitioning the maritime industry towards a CE. These include the absence of a comprehensive maritime circularity framework, insufficient empirical evidence demonstrating advanced circular practices, and a lack of enablers such as digital infrastructure and stakeholder-specific metrics. Addressing these gaps is essential to reduce waste, enhance resource efficiency, increase value extraction, and create a sustainable future for the maritime sector.

To bridge these gaps, the central research question guiding this thesis is:

"How can a maritime circular economy framework be developed to enable circular practices, integrate digital infrastructure, and align stakeholder efforts for maximising resource efficiency and value extraction and therefore contributing to sustainability in the maritime industry?"

This research question reflects the knowledge gaps identified in the preceding section and provides a structured approach to addressing them. It serves as a foundation for exploring innovative strategies, tools, and case studies that collectively contribute to a circular transition in the maritime industry. By answering this question, the thesis aims to advance the adoption of CE principles across the sector and deliver practical, actionable solutions to its unique challenges.

2.6 Chapter Summary

This chapter provided a comprehensive overview of the current state of the literature, identified the existing research gaps, and outlined the potential for novel contributions to address these gaps. It also provided the overarching research question.

3 Methodology

3.1 Chapter Overview

This chapter first presents a general information on the maritime industry, its stakeholders and vessels' lifecycle. Then, the research methodology and the positioning of this PhD study are clearly displayed.

3.2 Maritime Industry – General Info on Lifecycle and Industry Stakeholders

Maritime transport is the backbone of the global economy since it moves over 80% of world trade by volume (Stopford, 2009; UNCTAD, 2023), which is predicted to triple by 2050 (UNCTAD, 2022b). However, with the increasing demand for the maritime industry, the emissions caused by the industry will also rise across all stages of the life cycle. Recent estimates show that 10-15% of SOx and NOx emissions come from shipping, and that number will go up by 2050 unless serious steps are taken (Bjerkan & Seter, 2019; Zis & Psaraftis, 2019). Currently, the maritime industry aims to reduce its operational global greenhouse gas (GHG) emissions. It is going through a transition period to meet the demands of the UK, EU, and IMO on the net-zero targets. Therefore, the industry has pledged to lower its operations' GHG emissions by 50% by 2050 (IMO, 2018b; Milios et al., 2019). It has recently hiked its goal to at least 20% GHG emission reduction by 2030 and 70% reduction by 2040, ultimately expecting net zero by or around 2050 (IMO, 2023). Currently, the academia mainly focuses on lowering emissions and utilising renewable and green fuel sources in the ship operation stage by replacing fossil fuels. This is because the majority of GHG emissions are produced during the operation. However, this situation should not undermine the importance of shipbuilding and circular end-of-life options, as they are vital elements in the maritime industry's sustainability. The maritime industry needs to address sustainability, especially in conserving limited raw materials, through CE principles throughout the entire lifespan of vessels. The circular economy has gained significant attention as a potential answer for the maritime industry's multifaceted challenges. It offers an avenue to meet the industry's challenging environmental goals, such as decarbonisation or net-zero targets, and opens up new economic opportunities.

Currently, the shipbuilding industry generates 42,600 jobs and provides £2.8 billion to the UK economy (NSO, 2022). The shipbuilding operations mainly involve hull construction, outfitting, commissioning, testing and delivery. Even a basic cargo ship is equipped with valuable onboard components such as the main engines, auxiliary engines, compressors, pumps, navigation equipment, electronics, computers, etc. Today, the average economic life of cargo ships is around the 20–25-year range. For instance, Figure 3-1 shows the average age of the merchant fleet, and Figure 3-2 illustrates the average demolition age on top of the fleet age of containerships, as an example.

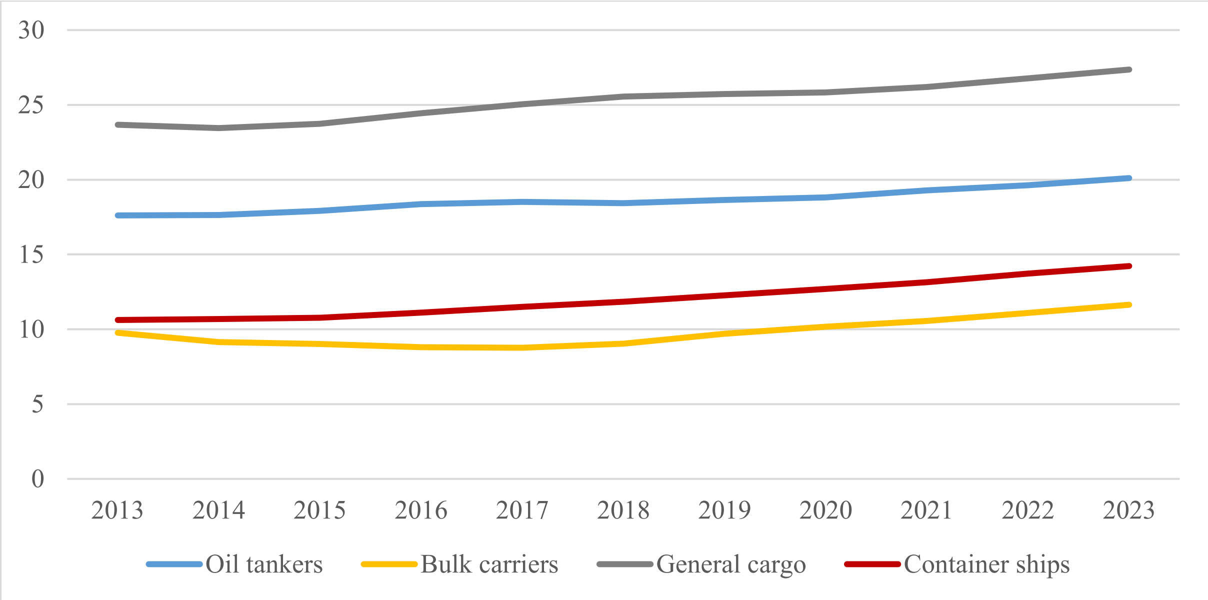

Figure 3-1: World merchant fleet age by ship types (Okumus et al., 2024b; UNCTAD, 2022a).

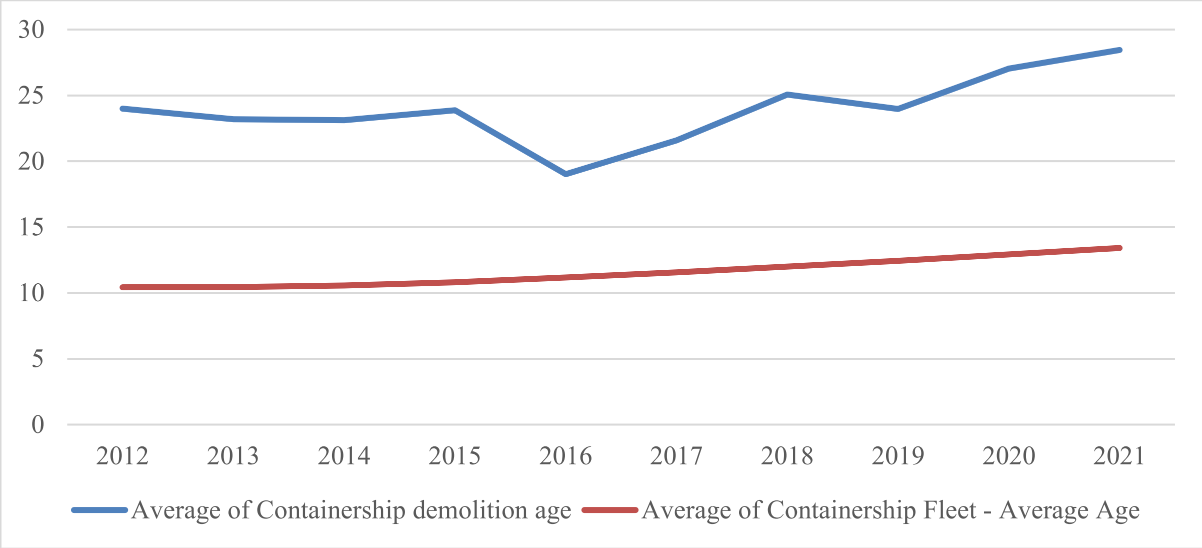

Figure 3-2: Average fleet age and demolition age of containerships (Clarksons, 2022).

The maritime industry is a unique sector comprising various stakeholders that design, build, operate and scrap the vessels or other floating bodies, or supply service, governance or equipment to these stakeholders (Milios et al., 2019). One unique aspect of the maritime industry is that the average lifespan of vessels is significantly longer than that of other heavy industries (Gunbeyaz, 2019; Hiremath et al., 2015). In the long lifespan of vessels, different stakeholder groups carry out specific functions to ensure safe and steady operation. The overall steps of a ship's life cycle are:

- Initial planning and design,
- Shipbuilding process (Contract, production, equipment purchase, construction and delivery)
- Operation
- Repair and Maintenance
- End-of-life

As shown in Figure 3-3 a linear flow describes the current practices realistically. This is due to the reasons explained later in this research. Overall, the link between end-of-life and new design or construction is missing in the maritime industry due to several reasons, including but not limited to lack of awareness in the industry, regulatory barriers, the long life of marine assets, the lack of a reliable reverse supply chain, and poor end-of-life practices. Moreover, conflicts arising from diverging interests among stakeholders present a significant barrier within the industry.

These challenges highlight the need for a holistic and comprehensive approach to address end-of-life issues in the maritime industry. At this point, Figure 3-4 shows the connection between the five main lifecycle stages of vessels (expanded from Montwiłł et al. (2018)) and maritime stakeholder groups (SSI, 2021): In the figure, green corresponds to a strong connection, while yellow means a moderate connection, and white cells indicate no direct affiliation (DIVEST, 2011). This section will provide a concise overview by introducing the lifecycle stages and the roles of corresponding stakeholders at each step.

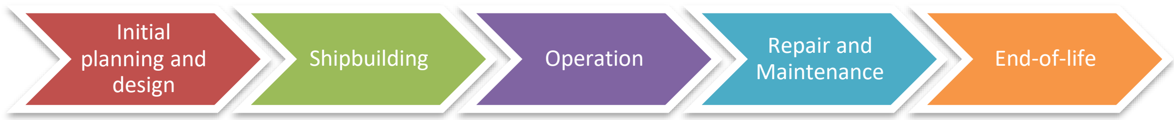

Figure 3-3: Vessels lifespan according to the current practices

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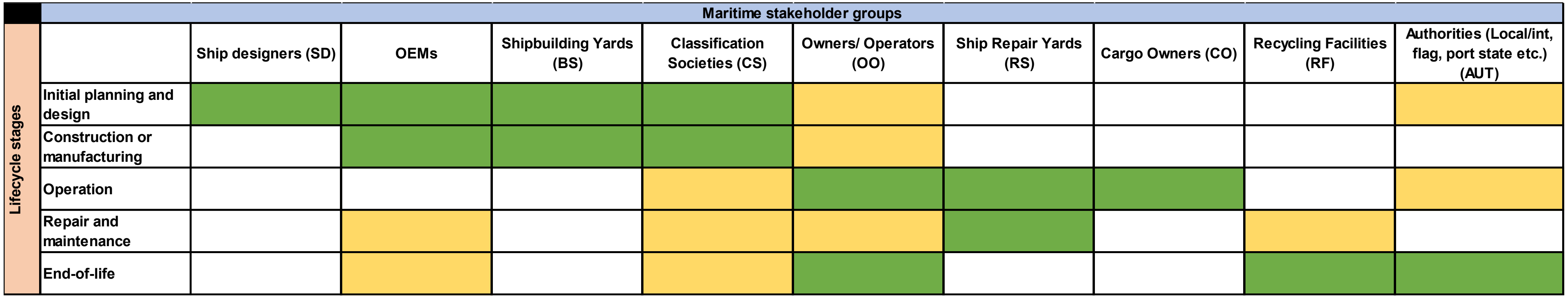


Figure 3-4: Connection between vessel lifecycle stages and maritime stakeholder groups.

3.2.1 Initial Planning and Design

In this step, the shipowner decides the requirements, such as the type of ship, the route it will serve, the conditions under which it will work, the crew size, etc. Following the identification of the vessel's needs, the shipowner will start making detailed plans by involving naval architects, consultancies, and, in some cases, universities or research institutes, design offices, and shipyards. During the design stage, there are two main approaches. One is basing the design on similar designs (by incorporating changing technology, regulations, or other factors), and the other is creating a new design from scratch. The former approach is usually preferred for commercial vessels. At the design stage, the overall characteristics and specifications of the vessel are determined, including the overall dimensions, speed, layout, and list of equipment and machinery (referred to as the maker's list).

In some cases, during these discussions, a broker might be involved from both the shipowner and the shipyard. It is also essential to investigate the regulations and legislation that the ship should follow at this stage. Contacts and meetings with the classification society and flag state usually take place to ensure compliance with all necessary requirements and standards.

Apart from finalising technical agreements, securing ship financing becomes imperative at this stage due to the substantial investment involved. While the negotiation between the shipyard and shipowner takes place, the shipowner also negotiates with the financier (e.g., banks, investors, government bodies) to secure such financing. After securing funding and finalising the contract with the shipyard, original equipment manufacturers (OEMs), including engine and auxiliary systems manufacturers, participate in quotations and bids for the specified maker's list.

Overall, the stakeholders involved in this stage are:

- **Shipowner:** Ordering a new ship for the new service
- **Design office, naval architects:** responsible for the design, equipment, and machinery decisions.

- **Consultants, universities, and research associations:** supporting the owner and designer during the design and research stages.
- **Shipyards:** involved in the contracts and detail design parts. Once the contract is signed between the parties, the shipyard is more involved in the design.
- **Original Equipment Manufacturers:** Manufacturers are involved at this stage to bid for the equipment on the maker's list.
- **Financers:** Grants the necessary financing for the planned ship.

3.2.2 Construction Stage

Once the agreement for the ship is done and the contract is signed, the production design and detail design stages start with the involvement of the shipyard's design team. The detailed plans for the construction, strength elements, outfitting, etc., are decided. Classification societies and regulatory bodies are involved at this stage to ensure that the ship meets the requirements in terms of safety for the crew, the environment, and the goods carried.

At this stage, the yard also purchases all the equipment and materials in the spec list. A mistake at this stage can impact the entire vessel's delivery timeline since all these equipment and material installations are tied to each other. Once the materials start to arrive, construction begins with the involvement of engineers, subcontractors, workers, supervisors, and consultants.

The launching takes place once the deck sections and the deck are constructed and the main machinery and equipment are installed. After this step, installation, painting, instrument checking, and other detailed work are completed. After the details are finalised, the sea trial and delivery steps take place.

To summarise, the following stakeholders are involved at this step:

- **Shipyards:** responsible for the construction and procurement of the material and equipment from the OEMs and local suppliers. Also manages the material flow within the yard, the arrival and storage of the material, and the equipment used in the particular vessel.

- **Subcontractor:** Supports the shipbuilding stage through various activities, e.g., construction involves supplying workers, consultancy, or expertise.
- **Original equipment manufacturers:** supply the equipment and machinery of the ship, ranging from the main engine to heating, ventilation, air conditioning units, electrical equipment, radars, and communication equipment.
- **Local suppliers:** Local suppliers are involved with the smaller purchases such as consumables (welding rods, HSE equipment, ropes, worker clothes, etc.).
- **The shipowner or the representative:** At this stage, the shipowner checks the progress in the building and makes the payments when the necessary checkpoints (e.g., keel laying, main engine installation, launching, delivery) are agreed upon in the contract.
- **Authorities:** Authorities check the shipyard for adherence to regulations, HSE rules, and other commitments regarding worker rights, taxes, etc.
- **Classification society:** The classification society checks the design and construction and ensures that the vessel meets the required standard. The society also ensures that the installed equipment on board the ship does not contain hazardous material for HSE.
- **Financers:** Financers might be involved in financing the shipyards' operations and shipowners' loans at this step.

3.2.3 Ship Operation Stage

The ship operation is a complex life cycle step involving various groups. Shipowners might have different options for the operation: using the ship for their specific operation (e.g., IKEA now employs their container vessels as a response to the container shortage) for their own company's supply chain; alternatively, shipowners might use the ship to carry other customers' cargo through different arrangements, which are also known as chartering. Three chartering options exist: trip (or voyage), time, or bareboat charter. A trip charter is carrying the cargo for a single voyage, and the owner with the sole responsibility operates the ship; a time charter is a ship rented for a time period with shared responsibility with the customer; or a bareboat charter is the complete rental of the ship to the third party for operation. With all these options, the sole goal of the owner is to get a return on the initial investment, pay back the loan if applied for, and make a profit.

As mentioned above, various stakeholders are involved in this step;

- **Owner, Charterer, or Operator:** The owner or charterer operates the ship for profit or to provide the required transportation service. They are responsible for arranging cargo supplies for the crew and the vessel, ensuring the ship is up to the standards of the flag state, the port state, and the classification society. The owner/charterer is also responsible for the crew's well-being.
- **Ship Crew:** Responsible for the day-to-day safe operation of the ship in line with the rules, with the guidance provided by the owner or the charterer. The ship crew is also responsible for onboard repairs in case of a breakdown during the voyage. Ships keep an extensive range of spare parts onboard them to ensure that essential units are backed up in the case of such breakdowns.
- **Ports:** Ports serve ships, load and discharge cargo with port equipment (or facilitate space for the ship to discharge the cargo using the ship's own equipment onboard), and provide supplies to vessels. The countries (port states) in which ports are located regulate them.
- **Port state:** The port state is the nation's officers that the ships visit. The port state has extensive authority over the vessels and has the right to tie the ship if a defect or an inconsistency with the regulations is found. Such cases are costly for the ship's operation since they will delay the entire operation and schedule and cause demurrage payments to the cargo owners.
- **Flag state:** Every ship is registered to a nation (not necessarily the nation where the owner's company is located), and these nations also have requirements for crew safety, working patterns, taxes, minimum payments, safety, etc. The flag states also have the authority to stop the vessel from operating if the standards are not met. On the other hand, registering the vessel with nations with less strict requirements, known as flags of convenience, is very common in the maritime industry. These flags have less tax and fewer regulations for the owner.

- **Authorities and policymakers:** The maritime industry is heavily regulated due to its reputation for accidents (and heavy consequences for human life and the environment) and the hazardous working conditions for the crew. These regulations sometimes change to address a need after an accident or technological advancements. Whatever the reason, these regulations bring essential changes to shipowners for operation or the rest of the stages.
- **Brokers:** Brokers are intermediary parties that help shipowners find cargo. They are paid a percentage of the earned amount.

3.2.4 Repair and Maintenance

The repair and maintenance steps are usually taken simultaneously as part of the operation step. Still, considering the nature of the tasks involved, the purpose of this research, and the circular economy viewpoint, this step is separated to demonstrate its importance.

Ships work in extreme environments during their lifetimes for various reasons, such as rough weather conditions, challenging sea states, or hazardous cargo types. As a result, regular repair and maintenance are crucial to ensuring the safety, efficiency, and longevity of the vessel. Ships go through regular maintenance to make certain that the ship’s structure and machinery are up to standards and requirements to be safe for the environment and the crew. Every couple of years (depending on the flag, class society, and ship type), ships head to shipyards (to graving docks, floating docks, or berths) for maintenance and surveys. During this visit, the ship's hull is cleaned and repainted if necessary, machinery and equipment are inspected, and the ship's hull is inspected in detail for corrosion or other defects to ensure its water tightness and strength to withstand nature’s forces. These operations are usually conducted at ship repair yards.

In addition to the repair and maintenance, ships might also visit the ship repair yards for refitting or repurposing. For example, with the recent regulation change on NOx or ballast water treatment, many ships had to be refitted with the necessary equipment (such as scrubbers and ballast water treatment systems) to comply with the changing regulations. In addition to regulatory considerations, shipowners may find it necessary to modify their vessels’ primary objective or purpose in certain situations. KPS vessels are good examples of this. Karadeniz Powership Series are power barges converted from general cargo carriers to power ships to supply electricity to the power grid in various countries lacking infrastructure (Dasgupta, 2019).

Table 3-1 presents ship repair and maintenance activities and summarises their frequency, location, and durations as a reference (Jansson, 2016). And stakeholders involved in this stage are:

- **Owner or Charterer:** The owner or charterer is the decision-maker for the maintenance schedules, repair intensity, refit decisions, and the operation's funder.
- **Classification Societies:** Surveyors from the societies are responsible for inspecting and identifying the condition of the ship, its equipment, and machinery.
- **Ship repair yards:** Repair yards are responsible for docking, inspecting, repairing, and maintaining vessels. If the ship is in the yard for refit or repurpose, their responsibilities include these. The shipyard's design team might also be involved in the refit scenario.
- **OEMs:** Similar to the shipbuilding stage, OEMs supply the equipment and machinery for the ship.
- **Engineering consultant and designers if refit:** If the ship is refitted or repurposed, this might include profound changes that need to be inspected in detail or bring additional design changes. Therefore, these parties are involved if the vessel is refitted.
- **Ship crew:** The ship's crew takes part in ship repair and refit operations since they are running the vessel and are familiar with the systems. They liaise with the company contact, providing reports to the owner or charterer.

Table 3-1: Different types of ship repair activities, their frequency, typical location and durations, from Jansson (2016).

Milestones of ships lifecycle	Frequency	Location	Duration
Maintenance	Continuous	Any	n/a
Small-scale voyage repairs	Occasionally	At sea	Hours

Milestones of ships lifecycle	Frequency	Location	Duration
Onboard repair	Occasionally	Harbour	Hours, days
Planned dry-docking, ship overhaul	Two times in 5 years	Repair yard	~ 2 weeks
Large-scale retrofit & refurbishment	After 10-15 years of operation	Repair yard	~ 3-4 weeks
Modernisation (extends commercial life by another 20 years.	The first lifetime is usually 20-30 years	Repair yard	~ 3-4 weeks
Conversion, lengthening, transformation to another usage	n/a	Repair yard	~ 1-3 months
Emergency repair & damage repair	No schedule	Any	variable

3.2.5 End-of-Life (EoL) Stage

End-of-life is, unfortunately, the most ignored part of the ship lifecycle investigations. After the ship's economic life, when repairs or retrofits can no longer keep the vessel financially viable or safe, the ship is "recycled." This operation takes place at ship recycling yards, usually located in developing countries that need steel for infrastructure, construction, or other projects.

The end-of-life phase may not solely result from ageing but can also be influenced by global economic conditions or regulatory alterations. For example, during COVID-19, many cruise vessels younger than ten years old were sent to recycling due to financial concerns (high maintenance costs and bad publicity at the beginning of the pandemic) (NGO Ship Breaking Platform, 2022). Moreover, during the 2008 global crisis, many new ships were sent to scrap to minimise the financial losses. Another example would be the past prohibition of single-hull tankers, which compelled shipowners to dispose of these vessels at ship recycling facilities. Therefore, the decision to send to scrap is not simple; it is tied to several criteria and scenarios. In these cases, the shipowner sells the ship for recycling to minimise the losses by earning from the steel tonnage.

Unfortunately, the ship recycling industry is one of the most problematic parts of the maritime sector, with the hazards involved in the tasks, the vast range of hazardous materials from end-of-life ships (e.g., asbestos, TBT, PCB, heavy metals), the lack of awareness of the yard owners and the workers, and the damage caused to the environment due to irresponsible ship recycling practices. Even though, weight-wise 98% of the vessel is recycled, this number twists the situation and puts the industry in a place rather than its actual condition since most of a ship's weight comes from steel (Gunbeyaz, 2019; McKenna et al., 2012; van t'Hoff & Hoezen, 2021). Many types of equipment, machinery, and onboard items go underutilised due to a lack of knowledge among the ship recyclers. In fact, recycling is the lowest hierarchy of end-of-life in a circular economy (Gilbert et al., 2017; MacArthur, 2013). IMO's Hong Kong Convention and EU ship recycling regulation aim to improve the overall situation (Solakivi et al., 2021). The practical improvement, however, expected to take a long time.

In this step, the following stakeholders are involved:

- **Owner:** Gives the decision to scrap the vessel. The owner's decision is critical regarding where to send the ship since environmentally friendly and safer options generate less income for the shipowner. The owner might choose to sell to the cash buyer as well.
- **Cash buyers:** Cash buyers are the intermediaries or middlemen in the industry who buy the ship from the shipowner and sell it to the ship recycling facilities to overcome the legal barriers brought in by the Basel ban and the IMO.
- **Ship recycling yards:** Ship recycling facilities are responsible for the safe dismantling of the vessel, the treatment of hazardous materials, and the downstream management of the items on board the vessel.
- **Local community:** affected by the practices around the ship recycling facilities due to the pollution and contaminated food chain, but when conducted safely, the industry creates employment.
- **Policymakers:** Regulates the industry for health and safety compliance and adherence to the regulations.
- **OEM:** Their equipment ends up on the shores of the ship recycling facilities.

- **Steel/metal producers/melters:** Steel from the yards is delivered to this industry, and depending on the need, the steel is rerolled, melted, or directly reused.

The ship lifecycle is sophisticated and influenced by many of factors, elements, and stakeholders that interact throughout the process. Each stakeholder’s behaviour affects the implementation of the principles of circular economy in the maritime industry, along with the barriers created by regulatory, economic, and infrastructure challenges.

In response to public and industry stakeholders' concerns, ship recycling operations have been undergoing significant transformations. Table 3-2 below shows the legislation and regulations in recent years that cover the end-of-life stage of ships.

Table 3-2: Policies on waste management and end-of-life.

Policymaker	Year proposed	Regulation	Status
International Maritime Organization	2009	Hong Kong Convention for the Safe and Environmentally Sound Recycling of Ships	Coming into force Jun 26, 2025.
European Commission	2013	The European Union Ship Recycling Regulation No 1257/2013 (European Commission, 2013)	It came into force in 2018
Basel Convention	1989	Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (1992)	Effective 1992

3.3 Methodology

While some of the chapters (6 and 7) present their individual methodologies and approaches, this chapter employs a comprehensive approach to present the entire study and establish the relationships between the chapters. Accordingly, Figure 3-5 depicts the general methodology followed in this thesis. The methodology of this PhD research consists of two phases. The Phase I includes a literature review (Chapter 2), initial stakeholder engagement events to collect insights from industry stakeholders, and barrier and opportunity identification stages (Chapter 4) of the study. Phase II, on the other hand, is positioned as the implementation phase, where the proposed solutions (Chapters 5, 6, and 7) are developed and tested based on the findings from Phase I. This structured approach ensures a systematic and thorough exploration of the research problem and facilitates a well-rounded analysis of the data collected throughout the study.

As shown in the figure, the study begins with a literature review presented in Chapter 2. The literature review first delved into the CE literature and defined the circularity concept, its principles, and R-imperatives. The evolution of the CE concept, beginning from the 1970s to the present, is traced, highlighting key milestones and developments in the field. After that, CE practices in the maritime industry and other transportation industries are investigated. First, a comprehensive literature review was carried out regarding maritime circularity in Section 2.3.1, and then the current situation at ship recycling facilities in popular ship recycling countries was presented in Section 2.3.2. The application of advanced CE principles in the aviation and automotive industries was presented separately, and findings were used to compare the three industries in 2.3.3. Consequently, this chapter presented research gaps identified in the literature and concludes with the overarching research question.

Following the literature review, intensive stakeholder engagement events in the form of online and in-person workshops, semi-structured interviews, and questionnaires were held between 2021 and 2024 during this study. These industry interactions support the following chapters as they provide up-to-date insights from the broad maritime sector. The details of each engagement event in Phase I are summarised, and each event is associated with chapters in Phase II as presented in Table 3-3. The questions asked in those events are also enclosed in Appendix F.

Lastly, in Phase I, Chapter 4 focused on the barriers and opportunities of CE in the maritime industry. A comprehensive stakeholder engagement survey was prepared, reaching out to a substantial number of stakeholders to reveal the industry's current position. With a broad range of perspectives gathered, the chapter highlights key challenges and potential gains for advancing circular economy practices in the maritime sector. The findings in this section were combined with the identified research gaps in the literature review to develop novel solutions in Phase II that address the barriers and capitalise on the opportunities for implementing circular economy principles in the maritime industry. In fact, Section 4.5 introduces the maritime circularity framework proposed to address these challenges and promote sustainable practices within the industry. This framework provides a comprehensive guide for stakeholders to navigate the complexities of transitioning towards a circular economy model in the maritime sector. Phase II aims to comprehensively identify and pilot these solutions in real-world settings to test their effectiveness and feasibility, ultimately paving the way for widespread adoption of circular economy principles in the maritime.

Table 3-3: Stakeholder engagement event details in Phase I.

Stakeholder Engagement Events in Phase I			**Associated research strands in Phase II**
Event	**Date**	**Description**	
Questionnaire	Between 09/2021 and 12/2021	• 83 participants • Findings presented in Chapter 4 and support all strands in the Phase II.	• Chapter 5 (solutions & remanufacturing case study) • Chapter 6 (database and asset tracking) • Chapter 7 (metrics)
In-person interview	30/06/2022 @Tuzla, Istanbul	• 9 participants (4 from OEMs, 3 from shipyards, 2 from consultants). • Regarding advanced CE practices, digital infrastructure and remanufacturing.	• Chapter 5 (solutions & remanufacturing case study) • Chapter 6 (database and asset tracking)
Online workshop	12/12/2022	• 51 participants. • Outputs include an industry gap analysis, SWOT and PESTEL.	• Chapter 6 (database and asset tracking) • Chapter 7 (metrics)

Stakeholder Engagement Events in Phase I			Associated research strands in Phase II
Event	**Date**	**Description**	
In-person workshop 1	23/01/2023 @ Watermen's Hall, London	• 14 participants • Regarding CE enablers, asset tracking and CE metrics	• Chapter 6 (database and asset tracking) • Chapter 7 (metrics)
In-person workshop 2	20/02/2023 @ Cranfield University	• 8 participants from academia and consultancy backgrounds • Regarding decarbonisation and circularity transition of the maritime	• Chapter 6 (database and asset tracking) • Chapter 7 (metrics)
Online interview	14/10/2023	• 12 participants from ship repair and recycling industries • Regarding the equipment tracking and database systems	• Chapter 6 (database and asset tracking)

As the first stand of Phase II, in Chapter 5, technology and strategy solutions for a circular maritime industry have been explored in depth. Then, current practices regarding CE amongst well-known marine engine OEMs are examined, and the overall engine remanufacturing process is presented. Furthermore, an engine remanufacturing case study was carried out to provide real-world examples of how the restorative cycle can be achieved effectively. The case study provides the financial implications of implementing circular economy practices in the maritime sector, shedding light on the potential cost savings and long-term benefits for businesses. Additionally, it offers insights into the environmental impact of engine remanufacturing, showcasing the importance of sustainability in the industry.

Further in Phase II, Chapter 6 presents a novel database design that enables material passports to advance circular practices in the maritime industry. The database and the maritime asset tracking system concepts developed could serve as a bridging solution for existing merchant fleets and onboard assets. Before delving into the specifics of the proposed database, this chapter provides a stakeholder needs analysis, followed by a CE and digitalisation section. Moreover, a case study is provided to showcase the practicality of the database and then estimate the potential financial impact of implementing material passports in the maritime industry. This comprehensive approach highlights the potential benefits of integrating circular economy principles into traditional maritime practices, paving the way for a more sustainable and efficient industry.

The development of maritime stakeholder-focused circularity metrics is presented in the final strand of Phase II in Chapter 7. This chapter includes a comprehensive review of existing circularity metrics in the literature, followed by a stakeholder-focused circularity assessment to identify which CE themes should be monitored for each stakeholder group in the maritime industry. Then, definitions of each circularity metric developed are given, and the overall metric structure is associated with five major industry aspects. Lastly, Chapter 7 involves a case study demonstrating how circularity metrics can be utilised. The case study focused on ship recycling yards as a stakeholder group and applied to three shipyards. Lastly, their circularity performance scores were calculated, and their respective performances were compared with one another.

Chapters that form Phase II (5, 6, and 7) altogether form the maritime circularity framework created within this PhD research. Case studies in these sections focused on different maritime stakeholder groups, namely OEMs, ship owners, and ship repair yards, to touch as many stakeholder groups as possible during this research. Table 3-4 illustrates the details of case studies conducted in Phase II, including the verification approaches adopted. This approach ensured that the framework was not only theoretically sound but also feasible and relevant for real-world implementation within the maritime industry.

Table 3-4: Case study details in Phase II.

Phase II chapters	Case studies	Data input for the case study	Result validation method
Chapter 5 (solutions & remanufacturing case study)	Main engine remanufacturing	Engine factory specs from OEM Remanufactured engine test results and cost breakdown from the dealer.	Brand new and remanufactured units' performance comparison. Cost/benefit analysis based on present value of acquisition costs.

Phase II chapters	Case studies	Data input for the case study	Result validation method
Chapter 6 (database and asset tracking)	Asset tracking using developed database	Vessel details from ship owner. Onboard equipment information (condition, working hours etc.) from the ship's engineer.	Validation workshop with 12 experts from shipyards, ship owners, OEMs, and recycling facilities (enclosed in Appendix B).
Chapter 7 (maritime circularity metrics)	Tailored metrics application for shipyards	2023 business results including sales, waste generation, emissions, and lead times from ship repair yards.	Validation workshop with 27 experts from nine maritime stakeholder groups (enclosed in Appendix E) Five expert opinions using AHP for the case study (presented in Section 7.6.2)

Finally, the thesis is completed after presenting the discussion, and conclusions and future recommendations which are presented in Sections 8 and 9, respectively.

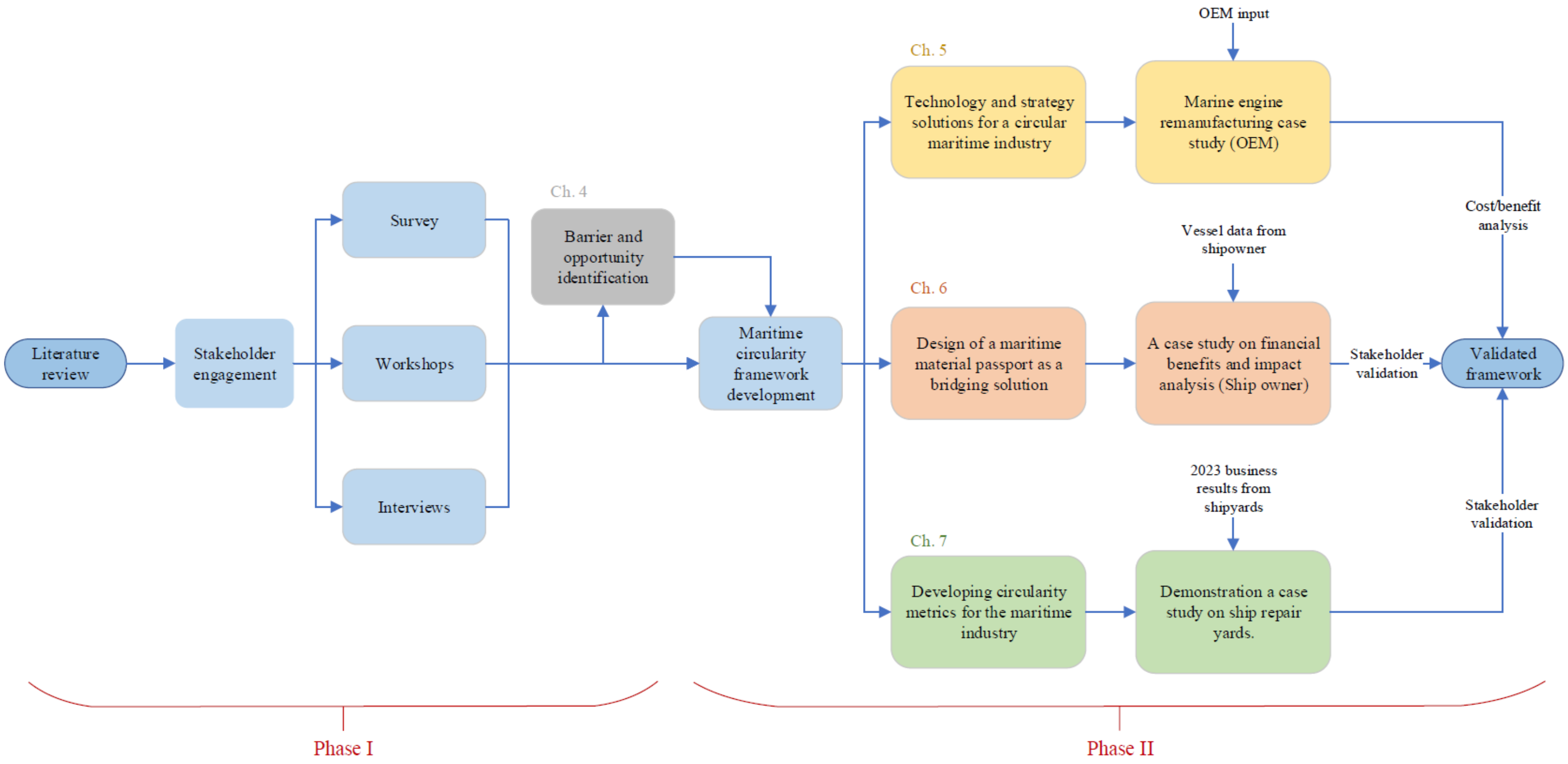


Figure 3-5: General methodology of the thesis.

3.4 Positioning of the Research

This research adopts Saunders' Research Onion framework to systematically position and explain its methodological approach, ensuring transparency and coherence across its design (Saunders et al., 2019). The framework's layers guide the progression from philosophical foundations to specific data collection techniques, aligning the research process with the objectives of addressing CE challenges in the maritime industry as shown in Figure 3-6.

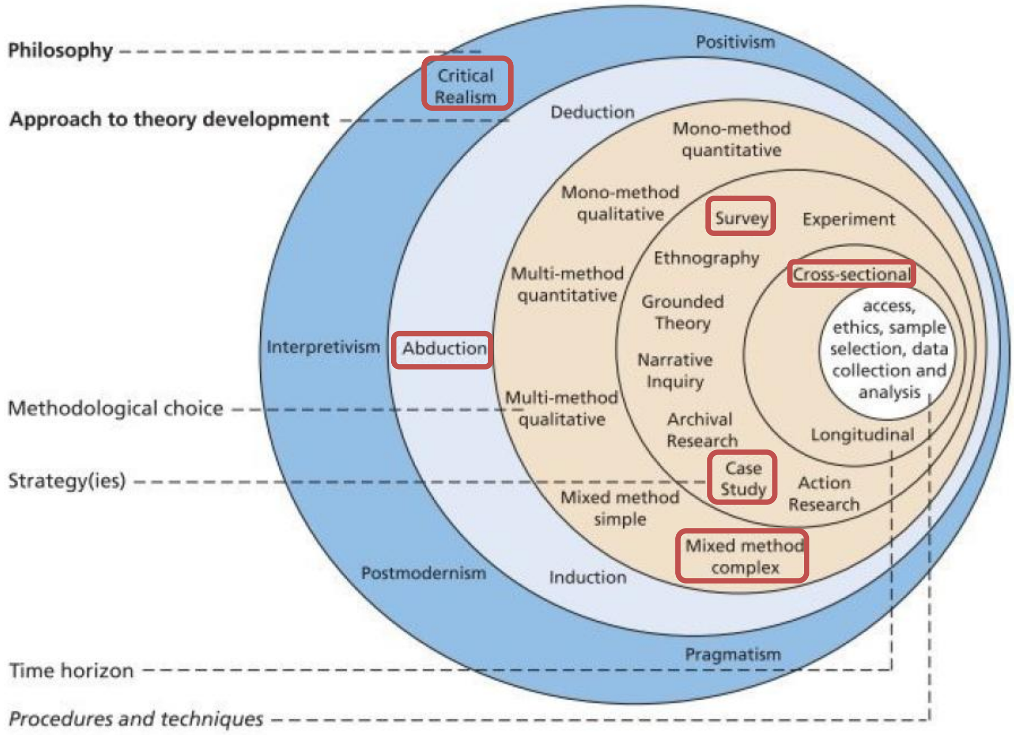


Figure 3-6: Research 'onion', adapted from (Saunders et al., 2019)

The research philosophy underpinning this study is critical realism, which focuses on uncovering the underlying structures and mechanisms driving the barriers and opportunities for CE adoption in the maritime industry. Critical realism bridges the gap between observable phenomena (e.g., stakeholder actions, industry practices) and the deeper systemic factors (e.g., regulatory, technological, and logistical dynamics) that shape these phenomena (Archer et al., 2013). This philosophy enables the integration of empirical observations with theoretical insights, facilitating a nuanced understanding of complex challenges and informing actionable solutions.

The study employs an abductive approach to theory development, which combines elements of deductive reasoning and inductive inquiry (Folger & Stein, 2017). The research begins with established theoretical frameworks related to CE and sustainability and iteratively refines them through insights derived from empirical findings, including stakeholder surveys, interviews, and case studies. This cyclical process of moving between theory and data ensures that the developed maritime circularity framework is both theoretically grounded and practically relevant.

A mixed-methods complex design forms the methodological backbone of this research, integrating both qualitative and quantitative methods to capture the multifaceted nature of CE in the maritime industry. Quantitative surveys provide a broad and generalisable understanding of stakeholder perceptions, industry practices, and key barriers, while qualitative methods—such as semi-structured interviews, workshops, and case studies—offer deeper, context-specific insights into the operational and strategic dimensions of CE adoption. This methodological combination enhances the robustness of the findings and allows for a comprehensive exploration of the research problem.

The primary research strategies employed are surveys and case studies. Surveys were distributed to diverse maritime stakeholders, including original equipment manufacturers (OEMs), shipyards, and shipowners, to collect data on their awareness, attitudes, and readiness for CE transition. Case studies, on the other hand, provided a detailed examination of specific scenarios, such as the remanufacturing of marine engines. These case studies served to demonstrate the practical feasibility, financial benefits, and environmental implications of adopting circular practices, offering concrete evidence to support the theoretical arguments.

The research adopts a cross-sectional time horizon, capturing data at a specific point in time to reflect the current state of CE adoption and stakeholder perspectives within the maritime industry. This approach provides a snapshot of prevailing attitudes, practices, and challenges, which serves as a foundation for proposing actionable strategies and future directions.

Data collection and analysis in this research were designed to be multimodal, combining structured surveys, semi-structured interviews, stakeholder workshops, and detailed case study examinations. Quantitative data were analysed using statistical techniques to identify trends, relationships, and significant findings, while qualitative data were subjected to thematic analysis to uncover deeper insights into stakeholder experiences and perceptions. In the case studies, financial modelling and comparative analysis were employed to quantify the economic benefits of CE practices, adding an additional layer of rigour and practicality to the findings. This multimodal approach ensures the triangulation of data, enhancing the validity and reliability of the results.

By situating the research within Saunders' Research Onion framework, this study demonstrates a coherent and well-structured methodological approach. Each layer of the framework aligns with the overarching goal of developing a maritime circularity framework that facilitates the transition to CE practices, addressing the specific challenges and opportunities unique to the maritime industry.

3.5 Chapter Summary

The methodology and the positioning of this PhD research were presented in this chapter.

4 Barriers and Opportunities of the CE in Maritime Industry

4.1 Chapter Overview

This chapter, being the last stage of Phase I of the research, delves into the barriers and opportunities of advanced circularity in the maritime industry. A thorough maritime stakeholder survey is presented, and its findings are used to identify and articulate barriers by referencing the literature and questionnaire results. Finally, the potential opportunities of CE principles were clearly outlined, directly linked to the identification of high value and high potential onboard equipment in the maritime sector. This chapter has been partly presented in the Transportation Research Arena 2022 international peer-reviewed conference (November 2022) and published in the Transportation Research Procedia (2023) volume 72 as follows:

Okumus, D.; Gunbeyaz, S.A.; Kurt, R.E.; Turan, O. Circular economy approach in the maritime industry: Barriers and the path to sustainability. *Transportation Research Procedia* **2023**, *72,* 2157-2164. https://doi.org/10.1016/j.trpro.2023.11.701

Additionally, this chapter's content has been partly discussed in a white paper published by the University of Warwick as part of the Circular Economy Network in Transportation Systems (CENTS) initiative:

Okumus, D.; Gunbeyaz, S. A.; Karamperidis, S. Potential Impact of the Circular Economy Concept in Maritime Transport. *White Paper - Circular Economy Network+ in Transportation Systems,* University of Warwick. 2023. https://warwick.ac.uk/fac/sci/wmg/research/materials/smam/cents/activities/whitepapers/maritime.pdf

4.2 Comprehensive Questionnaire for CE Barriers and Opportunities

Stakeholder engagement events, such as questionnaires, workshops, and interviews, are essential for identifying barriers and uncovering potential benefits in the transition to a circular economy. Opferkuch et al. (2023) highlight that the circular economy necessitates significant shifts in business models, supply chains, and consumer behaviour, which can only be effectively addressed through collaboration with industry stakeholders. These interactions help reveal the specific challenges and obstacles faced by stakeholders, allowing the development of frameworks that are tailored to address these issues. Through engagement with stakeholders, researchers can also uncover the overall industry perception, concerns, and expectations from the circular practices, ensuring that the frameworks developed are grounded in real-world conditions and increasing the likelihood of successful adoption (Mishra et al., 2022). This collaborative approach enables a deeper understanding of the barriers to CE transition, leading to the solutions proposed in the thesis.

4.2.1 Purpose and Structure

As part of this PhD research, a comprehensive questionnaire was designed to capture the current situation in the broad maritime industry regarding the CE principles. This part of the study presented in this section had been funded by the UK's EPSRC (Engineering and Physical Sciences Research Council) and the CENTS (Circular Economy Network in Transportation Systems) network (Okumus et al., 2022). The questionnaire consisted of a wide range of questions to capture the following points:

- Awareness of advanced CE principles other than traditional recycling and shipbreaking operations,
- Current and potential advanced circular practice rates,
- Barriers to the successful implementation of CE principles in the maritime industry,
- Revealing the industry's capabilities and willingness towards CE principles,
- High-potential onboard components that are suitable for restorative operations,
- Industry perceptions of remanufactured parts and components,

- Concerns about circular products and equipment,
- Existing reverse supply chain practices,
- Current demand for used equipment.

This comprehensive questionnaire included shipowner/operator companies, new building and repair shipyards, ship design professionals, OEMs, ship recyclers, classification societies, academia, and local or international authorities, reaching out to 83 participants. The average participant has 10.5 years of experience in the sector, and Figure 4-1 represents the number of participants from different stakeholder categories. As shown in the figure, there is a diverse representation of stakeholders in the survey, indicating a wide range of perspectives and expertise contributing to the research. The experts were contacted through the author's network and the broader network of the University of Strathclyde's NAOME department via email, social media, and phone calls. All the data was collected during the period between September and December 2021. The geographic locations of the participants are also quite diverse: there were participants from the UK, Greece, Turkey, South Korea, Bangladesh, Malta, Germany, Denmark, the Netherlands, Norway, and Switzerland.

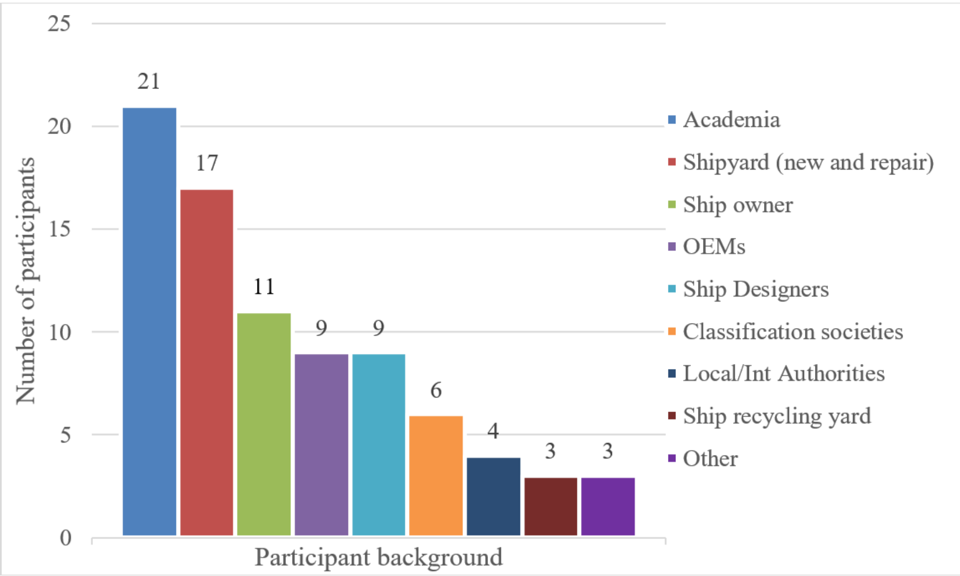
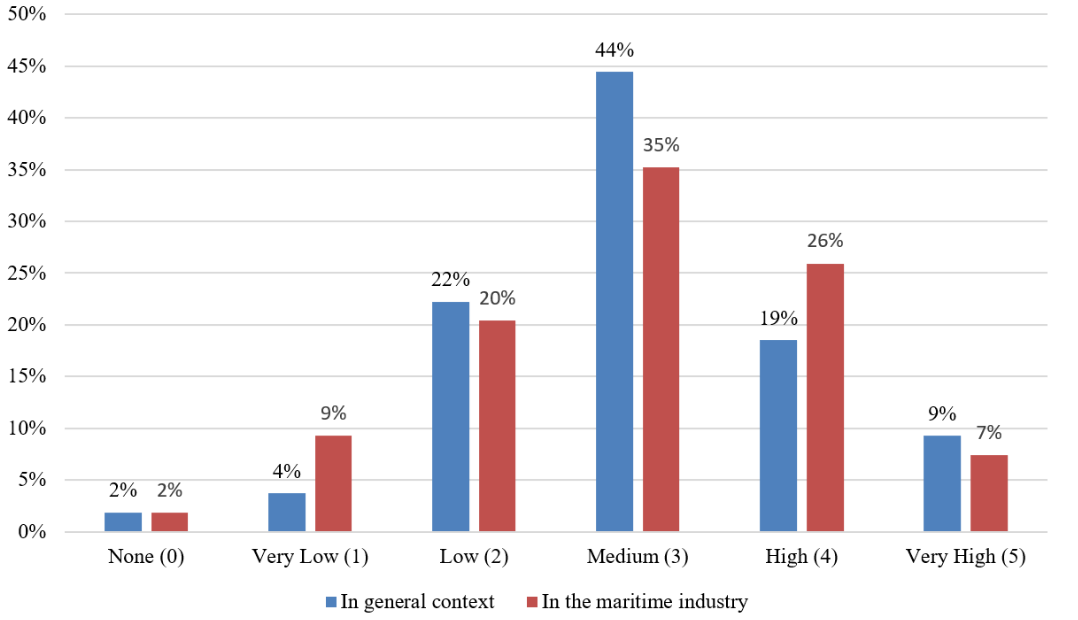


Figure 4-1: Distribution of the participants by their stakeholder groups.

The questionnaire had 33 questions in total, and it was tailored according to participants' backgrounds to discover the perspectives of different stakeholders. No question was designated mandatory in the survey; in this way, participants were allowed to skip questions on topics they did not feel competent. The questionnaire began with general questions; all participants could respond to the initial seven questions. Subsequently, each stakeholder group faces distinct questions, and the number of questions varies based on their responses. They are structured with follow-up questions to delve into the participants' viewpoints and identify conflicts. For instance, while an OEM participant would encounter (re)manufacturing capability-focused questions, a shipowner is questioned about their perception of remanufactured components. When shipowners express a preference against remanufactured products, this initiates two follow-up questions designed to pinpoint the primary reasons for their stance and explore potential factors that could sway their opinion in favour of remanufactured equipment. Appendix A contains all survey questions, and the subsequent section will delve into the detailed results.

4.2.2 Questionnaire Results

An introductory question in the survey revealed that 25% of the participants had never heard of the CE concept before this survey. The rest, or 75% of the participants, affirmed that they had heard it before. Then, the 75% of the participants were asked to rate their knowledge of fundamental circular economy practices such as remanufacturing, reusing, recycling (RRR), and the maritime industry. Figure 4-2 illustrates the results of their self-assessments, along with the statistical details related to the graph. The responses there reveal that, on average, the participants are slightly less familiar with the circular economy concept in the maritime industry (2.96/5) than in general (3.02/5). However, a significant group of people with high or better knowledge of the maritime industry accounts for one-third of the total. On the other hand, 31% of the respondents rate their knowledge level as low or worse in the maritime context.



Field	Minimum	Maximum	Mean	Std. Dev.	Count
In general context	0.00	5.00	3.02	1.05	54
In the maritime context	0.00	5.00	2.96	1.14	54

Figure 4-2: Participants' self-assessment of their knowledge of CE.

Figure 4-3 represents the participants' confidence in applying the circular economy practices in their businesses. Less than half of the respondents (45%) are confident that they have adequate background to implement circular economy applications in their businesses successfully.

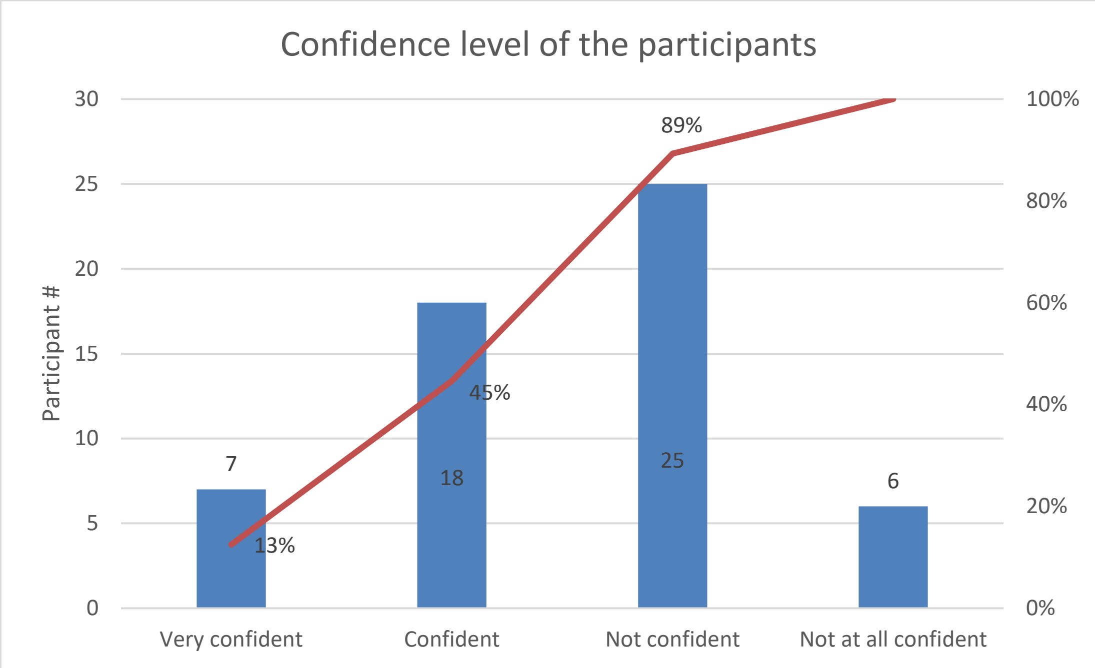


Figure 4-3: Confidence level of the participants.

Further in the questionnaire, the reusability, remanufacture, and repurpose potential of engines and hydraulic components onboard vessels are examined. These components were selected based on the previous research by Bletsas et al. (2017). The results are shown in Figure 4-4 below. According to all responding participants from various maritime industry stakeholders, these components have significant potential. 77% of the respondents rated main and auxiliary engines with medium, high, or very high potential, while 74% rated hydraulic components the same. In fact, for both cases, around forty percent indicated high or very high potential.

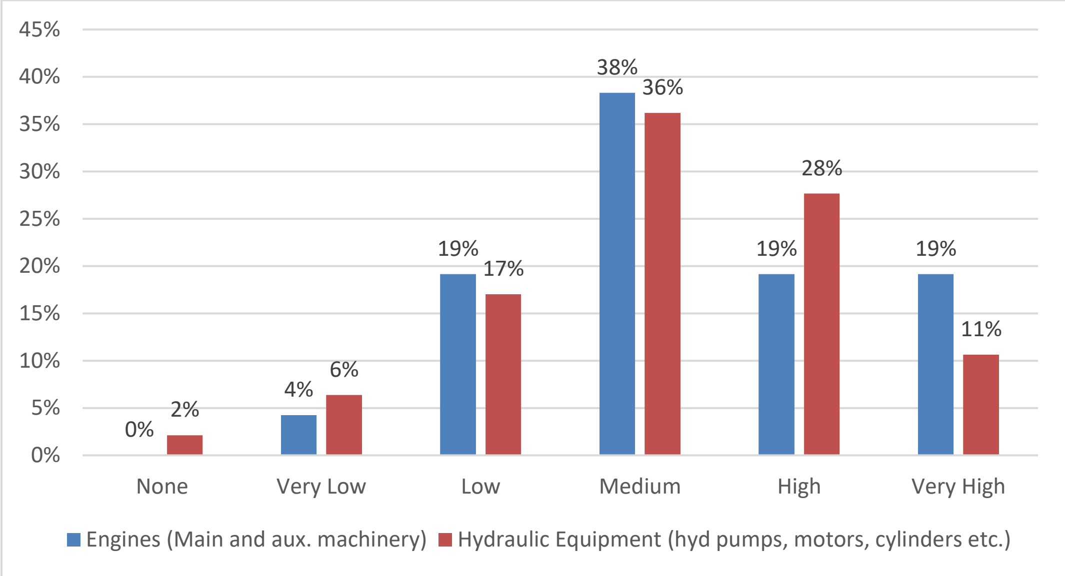


Figure 4-4: Reuse-remanufacturing and repurposing potential of engines and hydraulic equipment.

Shipowners and operators, new building and ship repair yards, experts from academia, designers, and engineering consultants are asked for their opinions on remanufactured components to discover whether they would prefer them. According to their responses in Figure 4-5, only less than a fifth of respondents strictly refused remanufactured options. At the same time, 41.5% stated that it would depend on incentives; another 41.5% found reman components favourable and affirmed they might prefer them.

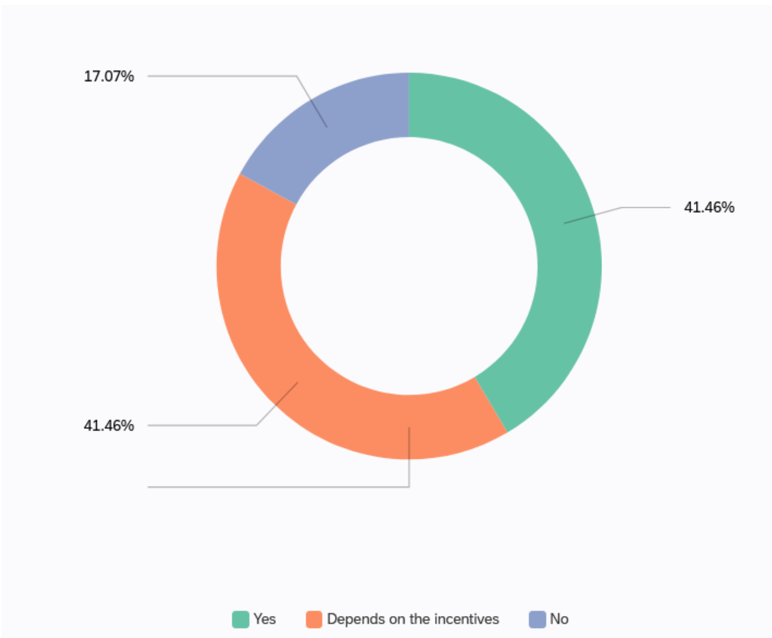


Figure 4-5: Would you prefer remanufactured components on vessels.

These results suggest a potentially positive perception of remanufactured products. A substantial portion of the industry tends to join that when convenient motivation is provided. This is particularly important because the respondents to this question are either direct decision-makers of such choices or have influence on the decision-makers in the industry. Therefore, their reaction might indicate a potential demand for remanufactured components in the future.

Figure 4-6 illustrates the factors pointed out by the sixteen respondents who stated that they might prefer remanufactured parts depending on the incentives in the previous question. The most important factor is the same warranty terms as a newly produced (brand-new) product, with price advantage and after-sales support coming in second and third, respectively, to offer additional assurance. Combining original warranty coverage and after-sales support promises from the interpreted results forms the basis for reliability and quality concepts. Therefore, to separate their importance from the financial aspect, another question was addressed to the participants within the questionnaire. Figure 4-7 illustrates the respondents' preference for remanufactured products, contingent on their matching reliability and quality with newly manufactured components. Strikingly, in this case, 89.5% of the decision-makers expressed that they would consider remanufactured products preferable.

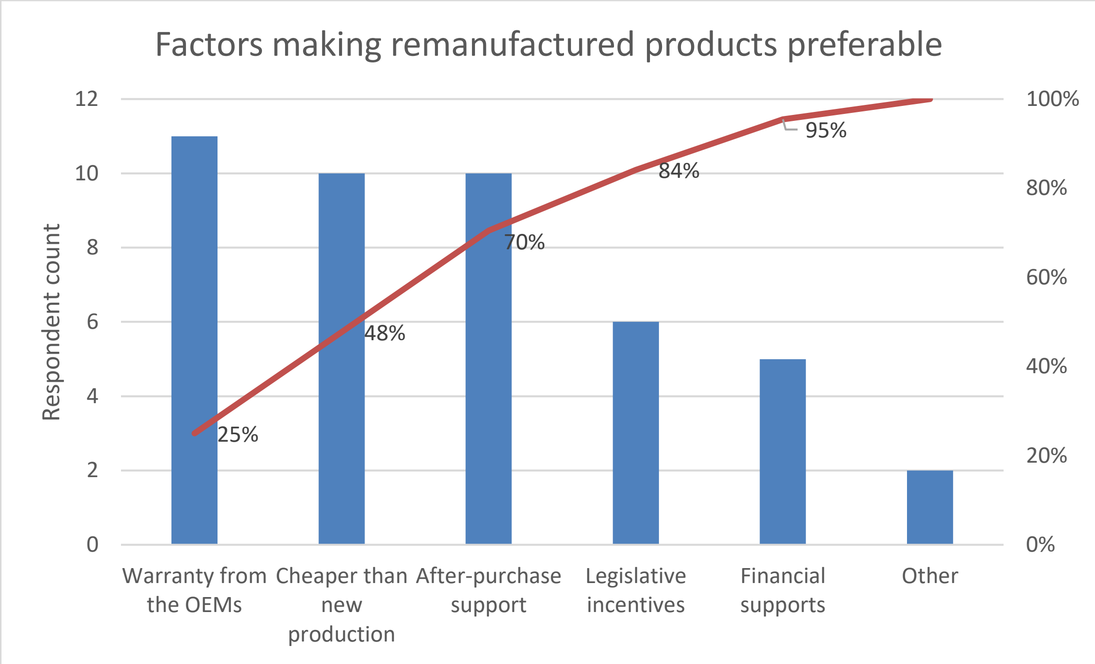


Figure 4-6: Factors positively affecting participants who might prefer RRR depending on incentives (Other – open-ended: engineering consultancy advisors and depending on the application).

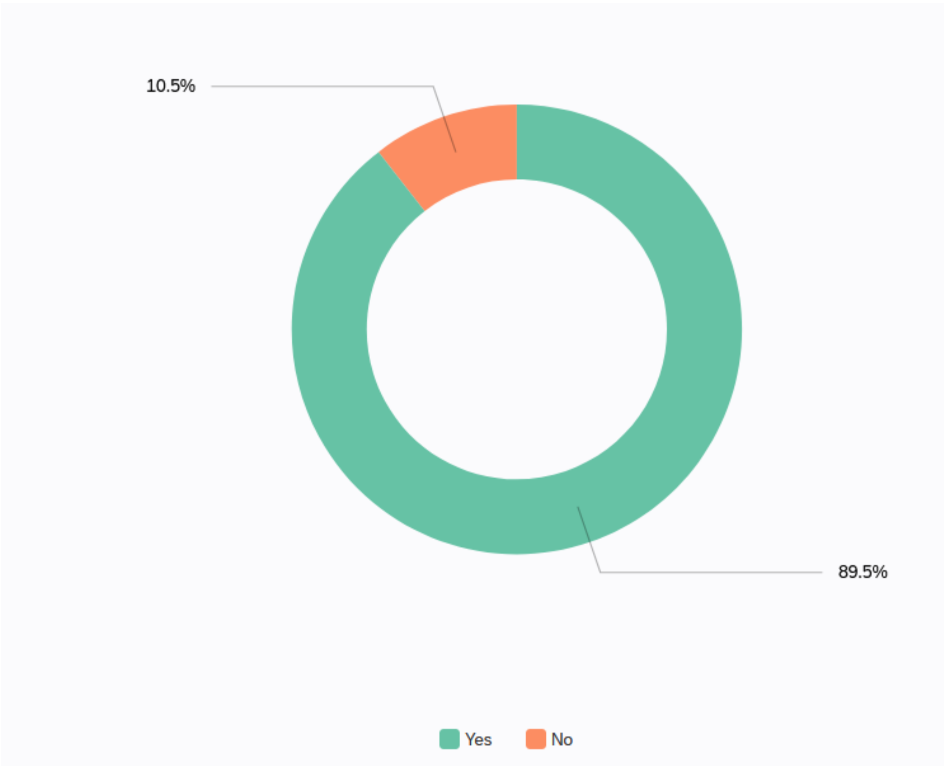


Figure 4-7: Would you prefer re-using, remanufactured or repurposed equipment if it offers the same reliability and quality as a newly manufactured product?

Subsequently, concerns about turning away remanufacturing options are examined. Even though this is a small portion of the whole sample—around 11% of the total—it is critical to address all concerns regarding remanufacturing. The respondents who gave negative feedback in Figure 4-5 and Figure 4-7 have expressed their worries, as illustrated in Figure 4-8. According to their input, the principal problem is still centred around reliability concerns. Other factors are listed as performance concerns and having expectations of no real economic benefit. So, when it is investigated further, a new drive that can overcome the reliability issues emerged in Figure 4-9; classification society approval. At this point, nearly all respondents who previously positioned themselves at a distance from remanufactured products indicated that class approval combined with appealing price advantages would change their minds. When combined with the same OEM warranty, the comeback ratio reaches 100%.

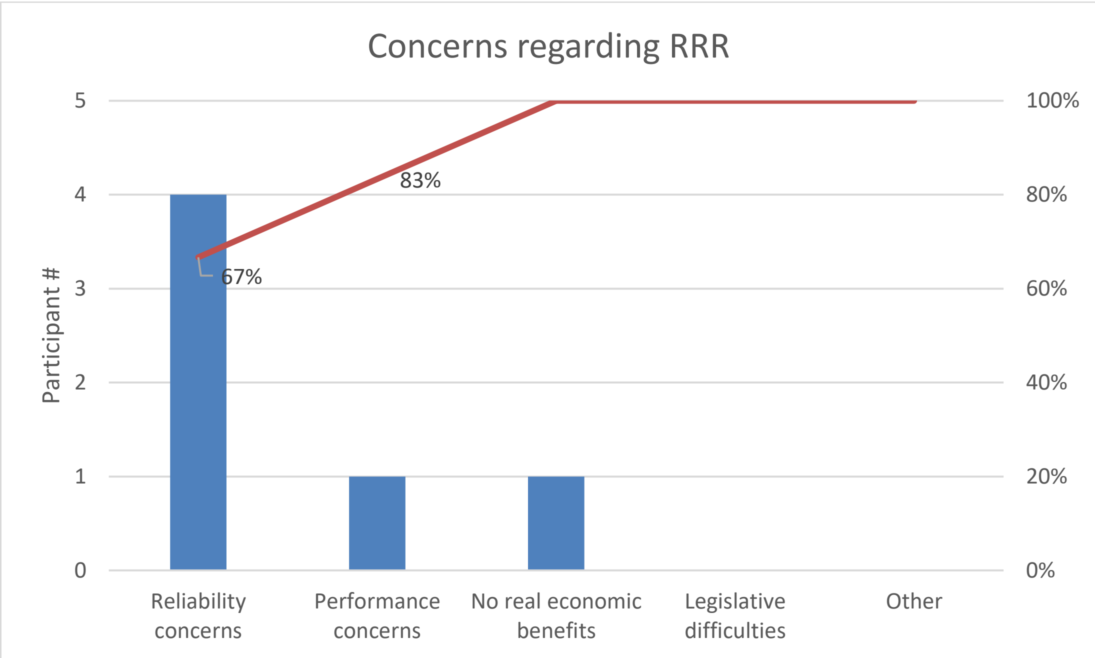


Figure 4-8: Concerns regarding reusing, using remanufactured or repurposed items.

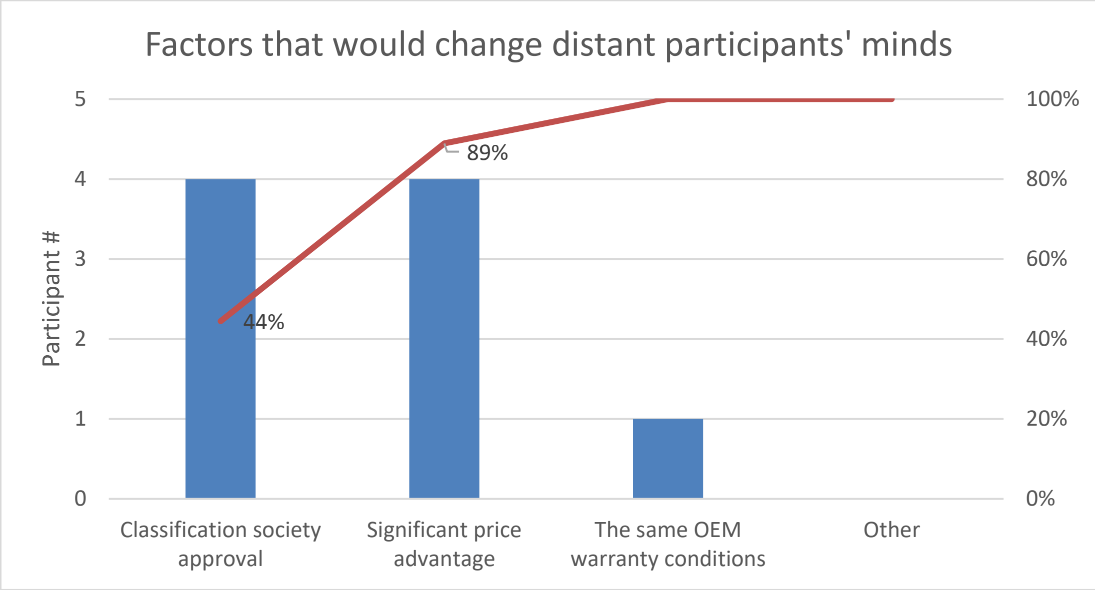


Figure 4-9: Factors that would change participants' minds.

Since circular practices and remanufacturing are strongly associated with the reverse supply chain, it is important to check used or second-hand market conditions. To that end, ship recyclers, OEMs, academia, ship designers, and engineering consultants are asked about the current demand for used components onboard vessels using a standard 1-5 Likert Scale. Table 4-1 illustrates the results, and summarises statistical measures. The complete engine is the most in-demand product, scoring a high (3.65/5) demand overall. Following that, hydraulic pumps and motors (3.35), cylinder heads (3.33), turbochargers (3.18), and engine blocks (3.12), respectively, all score medium to high demand. Then hydraulic cylinders are defined as medium in demand. Isolated aftercoolers or intercoolers, and crankshafts attract low to medium demand from the second-hand market.

Table 4-1: Current demand for end-of-life components in the used market.

Field	Minimum	Maximum	Mean↓	Std Dev.	Count
Complete engine	1.00	5.00	3.65	1.42	20
Hydraulic pumps & motors	1.00	5.00	3.35	1.28	20
Cylinder heads	1.00	5.00	3.33	1.20	18
Turbochargers	1.00	5.00	3.18	0.92	17
Engine block	1.00	5.00	3.12	1.08	17
Cylinders and other hydraulic eqp.	1.00	5.00	3.00	1.29	18
After/intercooler	1.00	5.00	2.94	1.03	18

Field	Minimum	Maximum	Mean↓	Std Dev.	Count
Crankshaft	1.00	5.00	2.75	1.03	18

Afterwards, the same respondents were asked whether it would be worth the RRR efforts considering the demands in the second-hand market. As seen in Table 4-2, for the selected parts and components, overall results indicate that professionals in the maritime industry agree that RRR efforts are worthwhile, with a mean of 3.56/5. Hydraulic components and complete engines are identified as the most agreed-upon products, followed by engine parts and subcomponents such as cylinder heads, engine blocks, turbochargers, crankshafts, and coolers, respectively.

Table 4-2: RRR efforts worth pursuing, considering the current used market.

		Complete engine	Engine block	Cylinder heads	Crank-shaft	After/ Inter coolers	Turbo-chargers	Hydraulic pumps & motors	Cylinders and other hyd. comp.	Total
1	**Strongly disagree**	2	4	1	2	1	1	2	1	**14**
2	**Disagree**	0	0	2	3	3	3	2	1	**14**
3	**Neither agree nor disagree**	6	4	7	5	8	8	3	4	**45**
4	**Agree**	5	9	4	5	3	6	7	9	**48**
5	**Strongly agree**	8	4	6	4	4	3	7	7	**43**
	Mean	**3.81**	**3.43**	**3.60**	**3.32**	**3.32**	**3.33**	**3.71**	**3.91**	**3.56**

Participants from recycling shipyards stated that all the abovementioned components disassembled during the decommissioning are sold through the second-hand market rather than scrapping. It is also noted that many businesses are selling used, dismantled components and parts around decommissioning yards and ship recycling facilities. A professional marine spare part dealer from Turkey stated that they are sometimes forced to compete with used parts released to the market from the Aliaga region, where most of the decommissioning facilities are located. There are various global online platforms where ship recycling facilities advertise parts and components they remove from end-of-life vessels.

Figure 4-10 shows which circular economy practices are currently implemented in the respondents' organisations from OEMs and shipyards. A total of 19 companies (9 OEMs and 10 shipyards) responded to this question. As can be seen from the figure, responses from OEMs' significantly boosted the overall results. Some OEMs have even declared that they focus on providing products as a service, which is quite an advanced CE practice. On the other hand, only a few shipyards—out of ten—stated their involvement in CE practices. After that, participants from OEMs and shipyards are asked to evaluate their ability to reuse/remanufacture/repurpose engines or hydraulic components, as shown in Figure 4-11. Those components are specifically included in the question, as they were previously revealed as the top-scoring onboard components regarding value and potential. Results indicate that, while almost all OEMs declared they could do it, some shipyards joined them. Around two-thirds (63%) believe they have the technical capabilities to remanufacture components onboard vessels. Therefore, the result shows that remanufacturing know-how exists in the industry, mainly among OEMs.

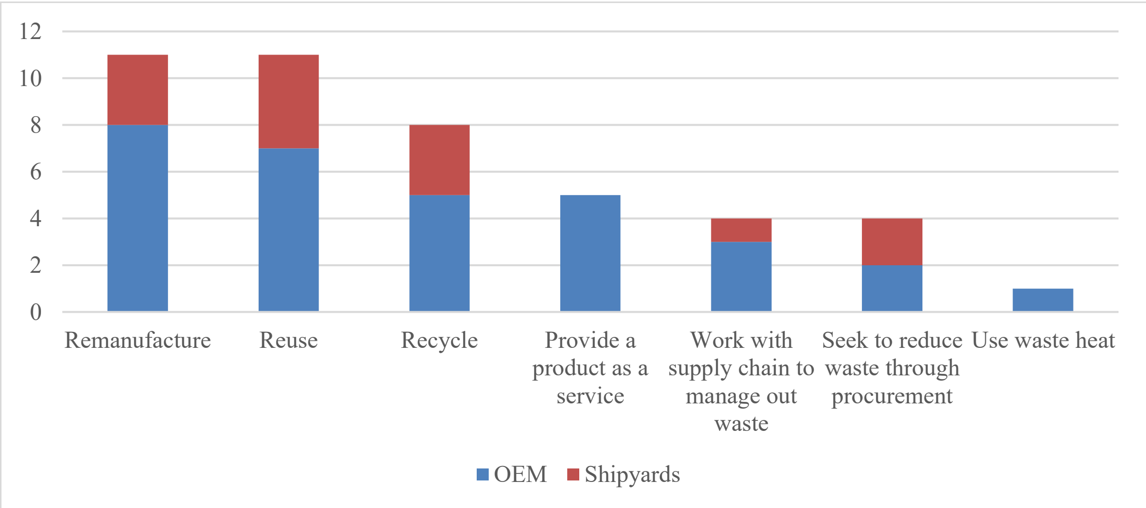


Figure 4-10: Currently implemented CE principles in the industry.

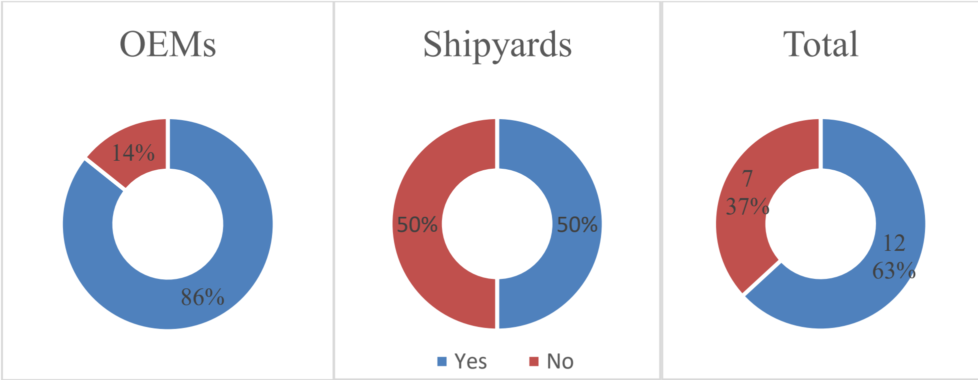


Figure 4-11: Response to the question *"are you able to RRR engines and hydraulic components?"*.

After discovering the ability to reuse, remanufacture, and repurpose valuable components in the industry, participants from OEMs and shipyards are further asked for their opinion and intentions towards RRR operations. As illustrated in Figure 4-12, 81.8% of them endorsed RRR operations and indicated that they would prefer to carry them out, which means there is a high willingness amongst capable shipyards and manufacturers in the industry.

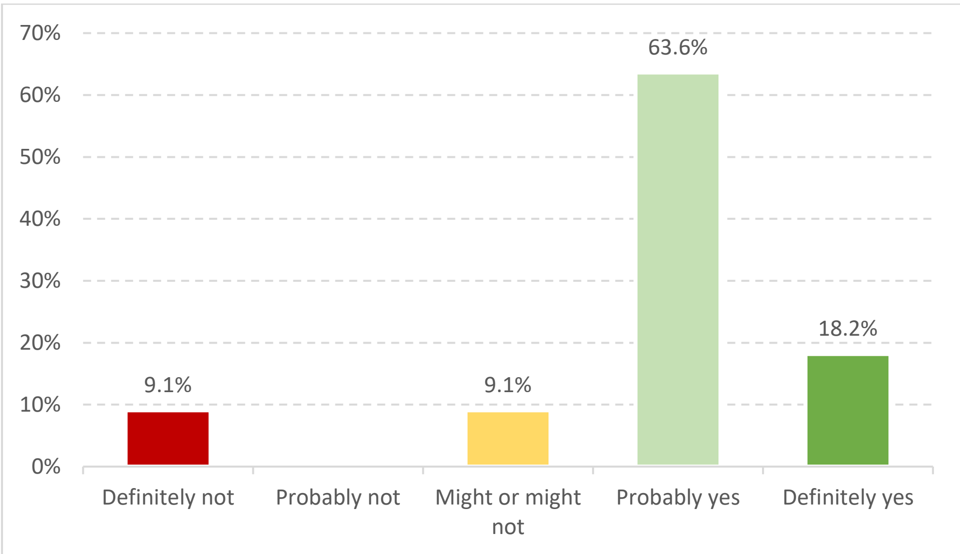


Figure 4-12: OEM's willingness to reuse, remanufacture, repurpose.

Restored assets based on circular principles can be exported to other industries. As long as it keeps materials and manufacturing energy in the loop and prevents waste generation, this is considered a part of CE. This practice is known as repurposing in the maritime domain, and the repurposing concept is investigated separately in the questionnaire. After decommissioning (or the ship recycling stage), the repurposing approach utilises parts and components of end-of-life vessels for uses other than their original purpose; this can happen in the same or other industries. Our discussions with ship recycling facilities revealed that, in practice, almost all repurposed parts and components are sent to other industries such as agriculture, electricity generation, etc. Participants from ship recyclers, OEMs, and academia rated the repurposing potential of main engines, auxiliary machinery, hydraulic pumps and motors, cylinders and other hydraulic components onboard vessels. Table 4-3 contains the summary of corresponding responses, including mean and standard deviation of the results. Auxiliary machinery and generator sets are the most suitable components for repurposing amongst the participants surveyed, as they received the highest ratings. This suggests a significant interest and potential for these components to be repurposed in other industries. According to participants in the repurposing section of the survey, Table 4-4 compiles a list of industries suitable for repurposing parts and components from marine vessels.

Table 4-3: Repurposing potential for components onboard ships.

	Minimum	Maximum	Mean↓	Std Deviation	Count
Aux machinery, gen-sets	1.00	5.00	3.40	1.23	25
Hydraulic pumps and motors	1.00	5.00	3.21	1.08	24
Main engine	1.00	5.00	2.92	1.11	24
Cylinders and other hydraulic equipment	1.00	5.00	2.80	1.33	25

Table 4-4: List of suggested industries where parts and components removed from marine assets can be repurposed.

Which industries would benefit from remanufactured/repurposed components on marine vessels?				
Main Engine	**Aux Machinery**	**Hydraulic pumps & motors**	**Cylinders and other hydraulic comp.**	**Other (please specify)**
Heavy industries – mining and construction	Electric power / energy generation industry	Construction and mining industries	Cranes	Batteries could be reused between industries in the future

Which industries would benefit from remanufactured/repurposed components on marine vessels?				
Main Engine	**Aux Machinery**	**Hydraulic pumps & motors**	**Cylinders and other hydraulic comp.**	**Other (please specify)**
Shipping industries in low-regulated countries	People in remote areas with limited access to electricity in developing countries	Factories and manufacturing industry	Factories	Tanks and electric motors can also be reused
Electric power generation	Automotive industry	Ship building and repair yards	Ports	
Offshore renewable energy	Floating and land based powerplants, production facilities	Fishing industry	Manufacturing industry	
Floating and land-based power plants	Shipyards	Agriculture	Automotive industry	
Land-based energy plants: cogen-trigen or landfill plants	Land-based energy plants, cogens, trigens, landfill plants	Aviation	Aviation industry	
Low cost vessels	Various electrical sites, substations, facilities as back up power source	Automotive	Energy plants	
		Manufacturing industry		

In the next part of the survey, the potential for collaboration among maritime stakeholders for a combined remanufacturing effort is investigated. In order to discover that, shipyards, ship recyclers, and OEMs are asked for their opinions on whether their organisation would participate in a remanufacturing collaboration across different stakeholder groups within the industry. By doing so, the potential maritime remanufacturing hub concept is investigated as shown in Figure 4-13. Although the majority responded positively, there is a considerable percentage of hesitant and undecisive participants. However, only five percent reacted adversely to the idea.

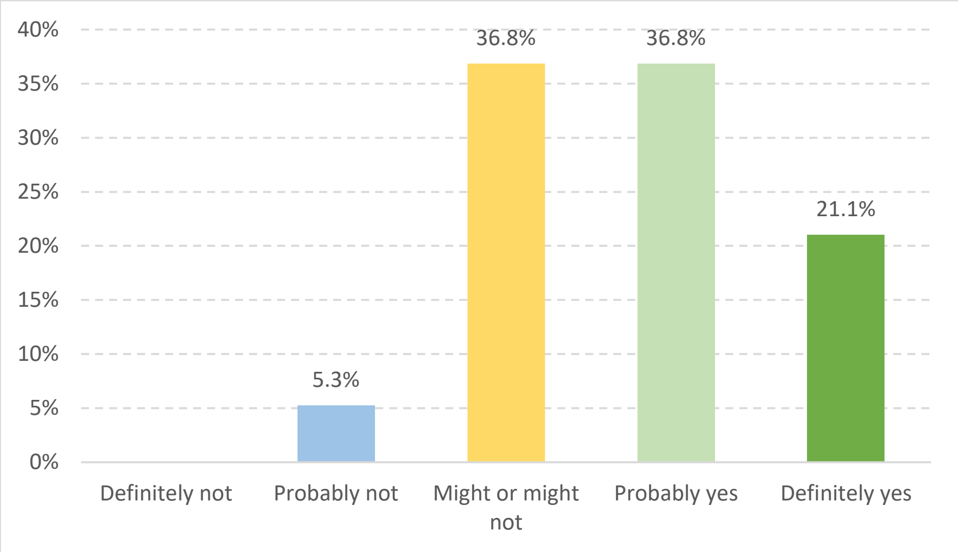


Figure 4-13: Would you participate in remanufacturing hubs (OEMs, Shipyards)?

Following that, OEM participants are further questioned about third-party remanufacturing companies. These companies might be a part of a large scale (potentially global) remanufacturing system, and therefore the OEM's attitude towards such businesses is critical. According to the results of our study, which are shown in Figure 4-14, maritime OEMs do not object to third party companies stepping in, as long as OEMs provide original spare parts and have the right to inspect and authenticate finished (remanufactured) products. Such a partnership resembles the dealership relationship many OEMs today have, except focusing on only remanufacturing.

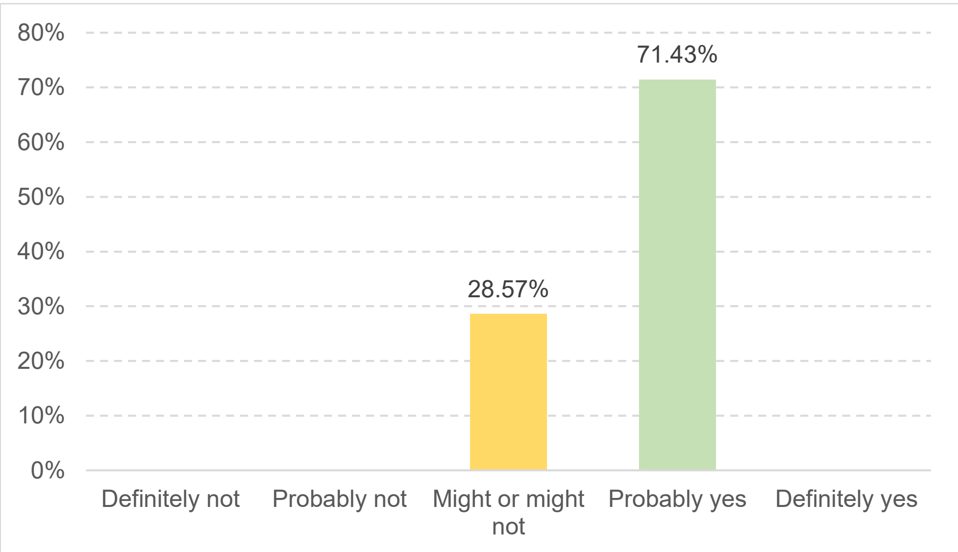


Figure 4-14: Would you cooperate with 3rd party remanufacturing companies if you provide the original parts and conduct inspections?

All participants from classification societies stated that OEM warranties and certifications are required to approve remanufactured components, just like a newly manufactured product. Half of them also expressed the need for additional third-party quality tests for remanufactured components.

Participants from local and international authorities are somewhat hesitant about regulation-wise support programmes for remanufactured components. On average, they indicate that it is neither possible nor impossible to provide support for remanufactured products.

Most of the participants from authorities, classification societies, and OEMs are not certain about a circular economy-focused study within their organisations in the near future; Figure 4-15 illustrates their expectations on the matter.

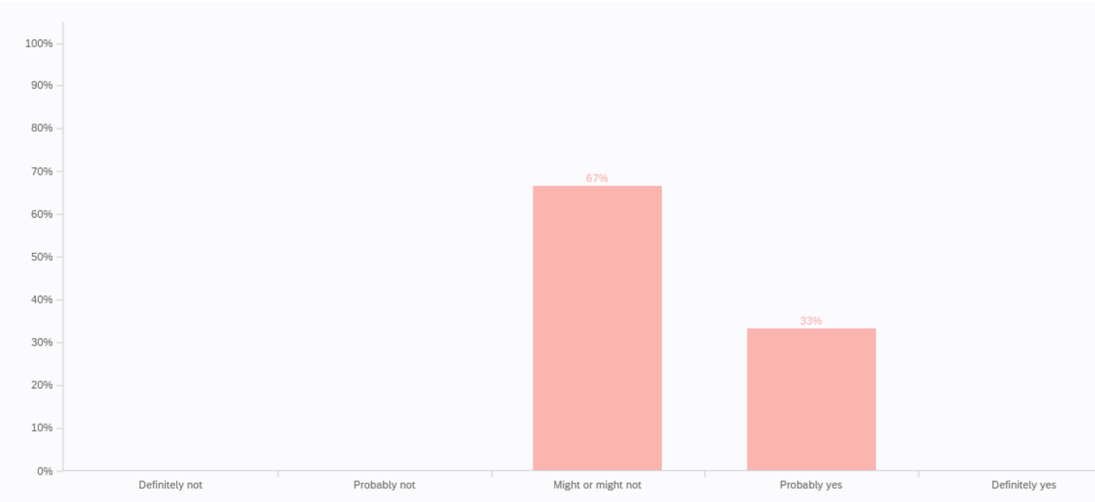


Figure 4-15: Expectation of further research on the circular maritime economy (Question was directed to authorities, OEMs, classification societies).

In their responses to earlier questions, the participants repeatedly emphasised the economic benefits of remanufacturing. According to maritime OEM participants, Figure 4-16 represents the potential economic savings on the acquisition cost of a remanufactured product compared to a newly manufactured alternative.

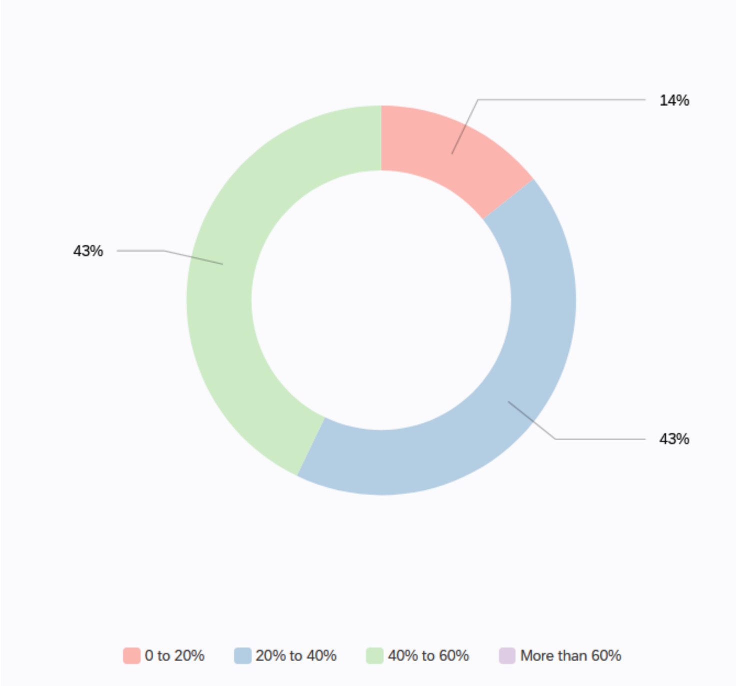


Figure 4-16: Expected savings on acquisition cost with remanufactured components (Question was directed to OEMs).

Around one-fifth of the researchers from academia and OEM professionals stated that they currently have ongoing studies on design for remanufacturing (see Figure 4-17).

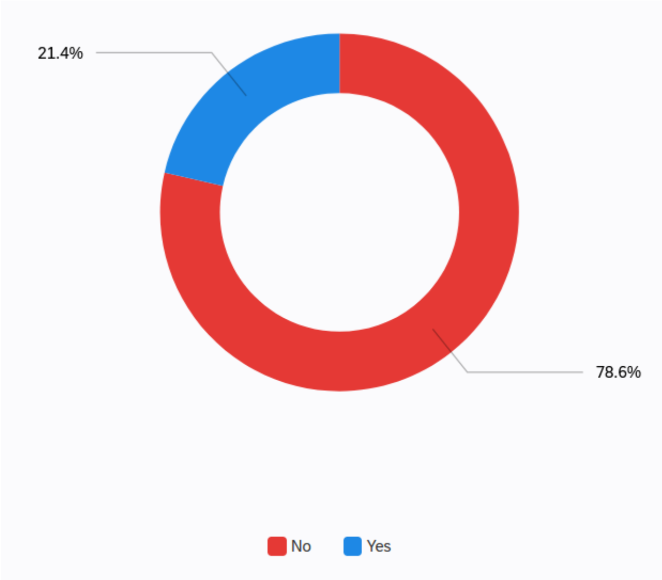


Figure 4-17: Ongoing studies for Design for remanufacturing from Academia and OEMs.

Later in the questionnaire, specific questions reveal the challenges of the core collection process. Figure 4-18 contains information gathered from ship recyclers, OEMs, and academia. According to the results, low demand for remanufactured products is the main issue for OEMs, while the know-how gap applies to recycling facilities. Regulatory restrictions and a lack of marketing opportunities are typically the next two critical issues.

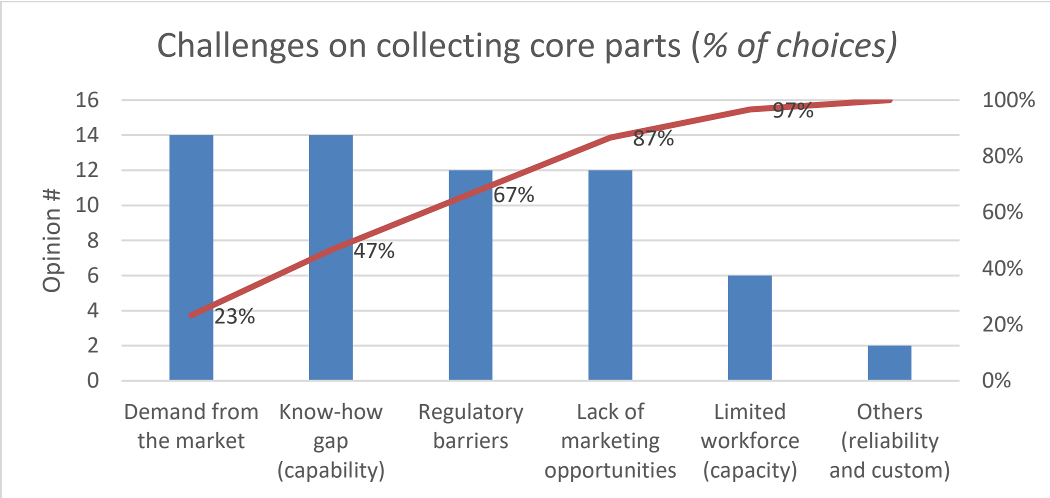


Figure 4-18: Challenges in collecting core parts.

Finally, the participants were asked where they think potential circular economy opportunities lie in the maritime industry. The top answer was remanufacturing, with a 71% rating; then, new raw materials and product or service design came up with 60% and 44% ratings, respectively. Figure 4-19 shows every opportunity that the participants mentioned in detail.

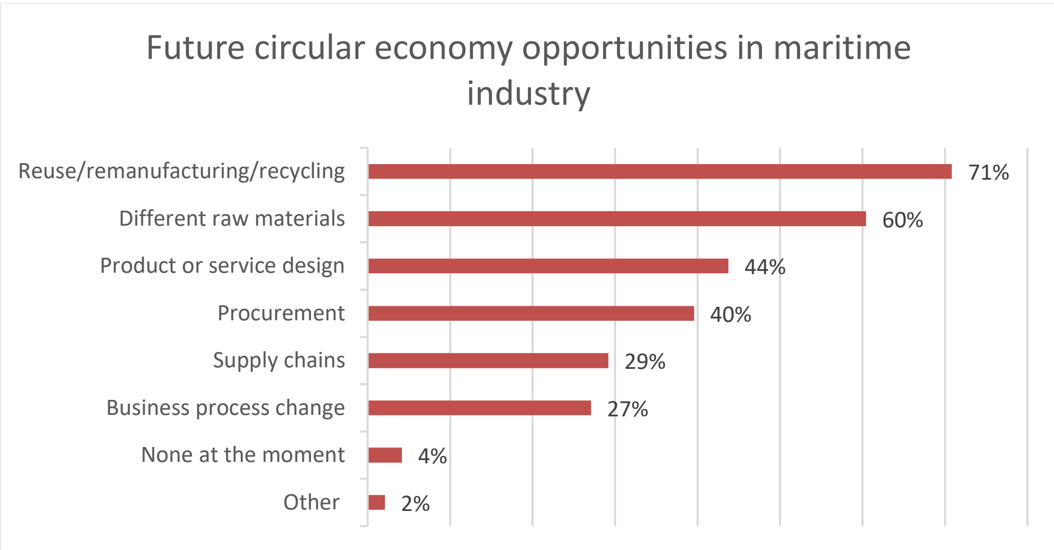


Figure 4-19: Future circular economy opportunities in the maritime industry.

Overall, the questionnaire captured a broad spectrum of viewpoints concerning maritime circularity. It explored stakeholder awareness, the general perception of circular products, existing capabilities, intentions, and other relevant factors. Moreover, barriers to the circular transition of the maritime and high-potential onboard equipment were also investigated. The survey results showed significant RRR potential in the maritime industry. There was also significant demand for used products, indicating an appetite within the industry for further advancements regarding CE principles if the barriers are effectively addressed. This implies a promising future for CE practices within the maritime sector, with opportunities for growth and innovation in sustainable solutions. As such, the following section will delve into the barriers to implementing CE practices in the maritime industry.

4.3 Barriers Identified to CE in the Maritime Industry

This section outlines the key barriers to the adoption of CE principles in the maritime industry, as identified through comprehensive stakeholder engagement and detailed analysis of the questionnaire results. These findings provide valuable insights into the specific challenges faced by various maritime stakeholders, offering a clear understanding of the most pressing obstacles to circularity in this sector.

While developing the questionnaire and interpreting its results, previous studies were considered to ensure a comprehensive and informed approach. For instance, (Milios et al., 2019) conducted semi-structured interviews with ten maritime stakeholders, focusing specifically on the Scandinavian maritime sector. Although their study provided useful insights into the barriers to CE adoption, its scope was geographically limited to Sweden and Denmark, which may not fully reflect the global nature and complexity of the maritime industry. Similarly, (Karvonen et al., 2015) concentrated on barriers to remanufacturing in Finnish industry, which, while informative, also suffers from narrow geographic and industrial limitations. The limited number of stakeholders involved in both studies may restrict the applicability of their findings to the broader maritime sector.

By building upon existing research while engaging a wider and more diverse range of stakeholders, this PhD research takes a more holistic and comprehensive approach.

The involvement of participants from different regions and stakeholder groups within the maritime industry provides a broader understanding of the barriers to CE adoption, offering a more globally relevant perspective. As a result, this research identifies five critical barriers that hinder the maritime industry's transition to a circular economy, as illustrated in Figure 4-20.

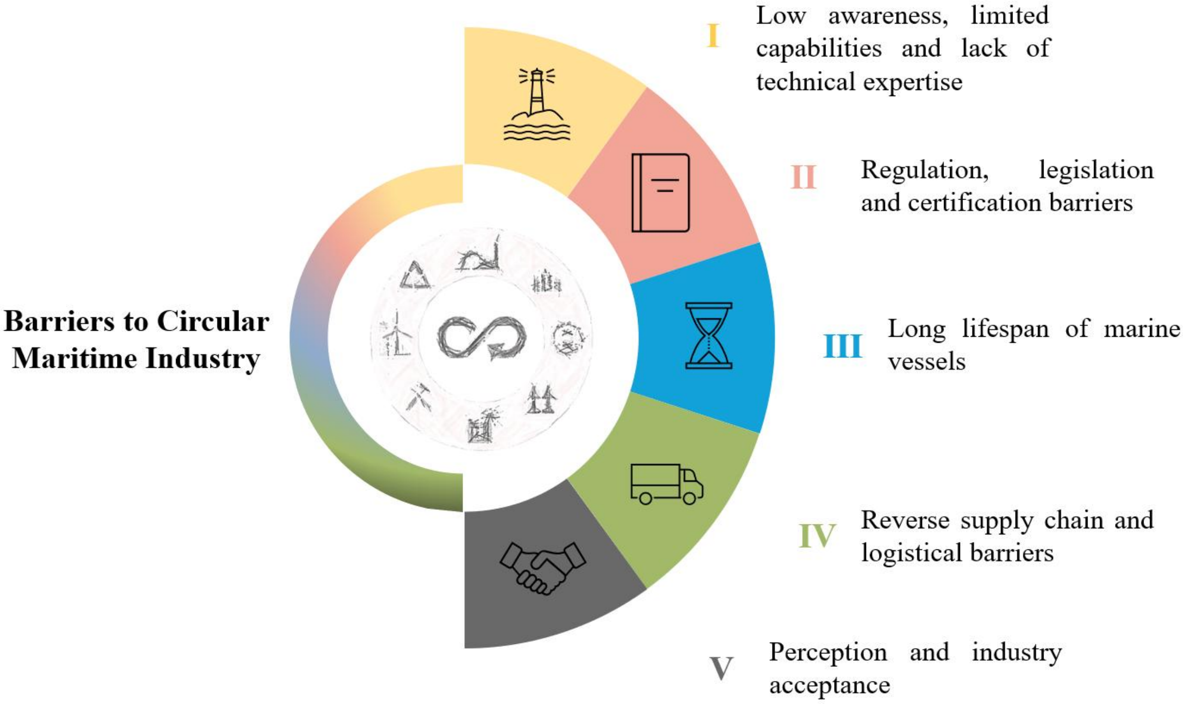


Figure 4-20: Barriers identified to maritime industry's circular transition.

4.3.1 Low Awareness, Limited Capabilities, and Lack of Technical Expertise

The overall maritime industry is unfamiliar with the CE concept, as the questionnaire shows that 25% of the participants have not heard of it before. Moreover, the participants' self-assessment shows that those who have heard about the circular economy have medium knowledge on average.

This also prompts an inquiry into the awareness of the yards. Low awareness of shipyards and recycling facilities directly affects the end-of-life practices of vessels, as it is reflected in dismantling methods and the reverse supply chain. The industry's poor expertise in this area and the general lack of awareness in the yards are evident in their dismantling practices. Currently, yards involved in repair and recycling are unaware of the potential value of the items they are dismantling. In many shipyards (build, repair, recycle), waste management companies take responsibility for treating the waste and taking care of the discarded equipment. According to Milios et al. (2019), the system for scrapping components is well-structured, but the take-back approach for 6R is lacking and non-existent. The questionnaire indicates that the approach is not non-existent but rather restricted to local capacities, such selling used parts in the Aliaga region through platforms like http://www.sahibinden.com or https://en.turkiyegemisokummarket.com. End-of-life equipment is usually redirected for scrapping rather than being returned to the manufacturer or directed towards remanufacturing. Also, since the current approach does not pay attention to quality, the equipment left for repair and reuse in the shipyards does not meet technical standards as in remanufacturing by OEMs.

There is a need to improve the skills of ship repair and recycling facility workers for removing components from end-of-life ships without damaging the core products, instead of torch cutting anything on board without proper assessment. More than half of the relevant participants (56%) raised this technical expertise gap in the survey. The quality of the items dismantled from vessels is difficult to ensure, which can increase the remanufacturing costs and the difficulty of the processes.

Furthermore, a sufficient volume of cores must be collected in good condition to establish reuse or remanufacture applications (Matsumoto & Umeda, 2011). The technical capacity and capabilities of recycling yards directly influence this requirement. Furthermore, since the maritime industry lags in practice, maritime equipment manufacturers' remanufacture and rebuild capacities are lacking (apart from the well-known engine remanufacturers, which serve other industries as well), especially compared to other sectors such as automotive. Therefore, there are challenges related to the restorative processes, and low awareness and know-how gaps might increase the cost and lead times.

4.3.2 Regulation, Legislation and Certification-related Barriers (Classification societies, Flag authorities etc.)

One of the most critical barriers to implementation is the regulations themselves. The maritime industry is heavily regulated with rules, regulations, and legislation to mitigate the negative impacts of past issues on the environment and human health. Ships must be registered with a classification society, which regulates the vessel on behalf of the flag state and ensures that the vessels' structures and the yard that builds (repairs or refits) the vessel comply with those rules. This is a critical part of the maritime circular economy approach, as it directly affects the fate of equipment. As part of their responsibilities, class societies check the certification of every item onboard a vessel, including new, used, and remanufactured items. Currently, classification societies ignore remanufactured items in retrofitting ships; instead, they prefer new components (Milios et al., 2019). According to International Association of Classification Societies (IACS) rules, for instance, each engine manufactured for marine applications must have a type-approval certificate and engine certificates. In order to carry out the aforementioned certification process, classification societies require a long list of documentation, including but not limited to technical drawings (e.g., engine cross-section, separate parts drawings, frame and bedplate welding, etc.), assembly plans, production specifications for castings, engine control systems, starting-fuel-lubricating-cooling-hydraulic systems, safety systems, operation and service manuals, and so on (IACS, 2022; Lloyd's Register, 2022).

Manufacturers are responsible for the certification process of new items. Certification is provided with the equipment, placed in the vessel's documentation, and handed to the shipowner by the shipyard upon ship delivery. There are typically no issues with this routine, straightforward procedure that the yards have used for years without complications. On the other hand, the problem starts when reusing or using remanufactured equipment. That will need to be re-certified by both the classification society and the OEMs before it can be put on board the vessels, which may create a conflict of interest between the original equipment manufacturer and third-party remanufacturer. Classification societies are also reluctant to re-certify used or remanufactured products since there is a lack of knowledge. In the survey presented in

Section 4.2, all participants from classification societies stated that in order to approve remanufactured components, OEM warranties and certifications are required, just like a newly manufactured product. However, there are currently no specific certification processes or rules established by classification societies for remanufacturing marine engines. Since the control over certification belongs to the OEMs, they may not decide in favour of third-party remanufactured parts in the maritime industry based on their authority. The re-certification costs, requirements, and standards are kept high as a deterrent, in addition to the actual legal requirements. However, the survey results show that OEMs do not object to third-party companies stepping in as long as OEMs provide original spare parts and have the right to inspect and authenticate the finished products.

Moreover, maritime industry regulations occasionally change to address the world's developments, requirements, or trends. Therefore, a good design or a product in line with the regulations ten years ago may become obsolete following a requirement change. Thus, used or remanufactured products may not satisfy current regulations. The most obvious example of this problem is the remanufactured engines, which are expected to be in the same condition as when they were manufactured as brand new products, but remanufactured or reused engines may not satisfy the current regulations, particularly in terms of exhaust emissions due to the IMO MARPOL (Annex VI) requirements (Tier III engines only in NOx Emission Control Areas). The old engines (Tier II) from end-of-life ships do not meet the requirements and require significant upgrades to comply, which costs a considerable sum of money. As a result, these engines are usually scrapped or disassembled for spare parts. On the other hand, the production year and the specifications of the used components determine if they can be used in the maritime industry or might still be useful for other industries or countries with less strict legislation.

4.3.3 Long Lifespan of Maritime Vessels

One unique aspect of the maritime industry is the longer average lifespan of vessels, which extends to 30 years (Hiremath et al., 2014). The extended lifespan of vessels presents challenges for transitioning to a circular economy. Maritime industry regulations evolve in response to global developments, requirements, or trends. Hence, a well-designed product from a decade ago or one that is compliant with previous regulations may become outdated due to new requirements. Consequently, used or remanufactured products may fail to meet current regulations due to changes in requirements. An exemplary case is remanufactured engines, which are required to meet exhaust emission standards per the IMO MARPOL (Annex VI) requirements, but may fall short of compliance.

Furthermore, the extended lifespan of vessels can disrupt the feedback loop for designers when the original designer or builder is no longer available. As a result, the lack of a learning process at the end of a vessel's life hinders knowledge transfer and improvement. Since there is no learning process, the "Design for X" approach is missing too. Additionally, the extended lifecycle results in ship owners having outdated components unsuitable for maritime industry use at the end-of-life stage. Or, even if it is suitable, the equipment might not be economical to use compared to newer alternatives in terms of operating costs. This creates further problems with component repair or remanufacturing, as they are not designed to facilitate this (Milios et al., 2019). However, we see an interest in this area, albeit low.

The long lifetime also causes issues in tracking the assets. So far, there is no database of equipment and components onboard the ships. In addition to this, the standardisation in the industry is very poor. The range of materials on board the vessel is vast, and every OEM, yard, or designer approaches the same system differently. This lack of standardisation also creates problems in the dismantling parts. Design for Remanufacturing (DfRem) can be a crucial element to challenge that; however, currently, there is only limited interest within the maritime industry. This vast range of materials and equipment also creates issues for the supply chain. Furthermore, this wide supply chain also prohibits effective communication. These two problems cannot be overcome without industry-wide application and collaboration.

4.3.4 Reverse Supply Chain and Logistical Barriers (and asset tracking issues)

Today, Asian shipbuilding yards dominate the new-built market, while Bangladesh, India, China, Pakistan, and Turkey dominate the scrapping market (UNCTAD, 2022b).

Therefore, the production and demolition locations are entirely different, which creates the issue of the core collection for restorative practices. Long distances and an underdeveloped reverse supply chain currently hinder the support of 6R principles.

Furthermore, the products decommissioned from the vessels are often not very well known and handled by ship recycling yards due to know-how gaps. These problems make it hard to set up systems for reuse or remanufacture because it's not possible to run these business models with a limited number of products from different places and unknown timing and amounts of returned cores (Jansson, 2016).

The long lifecycle of vessels, the lack of standardisation regarding advanced circular practices, and the diverse range of materials and equipment on board pose a significant barrier to asset tracking (including onboard equipment and components) in the industry. Milios et al. (2019) state that a shipping company tried to facilitate reuse and recycling effectiveness by mapping the components, but the extensive supply chain made this impossible. Moreover, the extensive supply chain prohibits effective communication. These problems can only be overcome through industry-wide application and collaboration.

4.3.5 Perception and Industry Acceptance

Another major challenge in the maritime industry is the perception of key stakeholders, such as shipowners or shipyards, regarding remanufactured, reused, and recycled (RRR) products. Shipowners and shipyards do not prefer using remanufactured or reused items for several reasons, such as concerns about reliability and performance. The survey results indicated that 20% of the participants strictly refused the option, while 40% requested incentives. Most shipowners are unaware that remanufactured products come with an extended warranty period. As mentioned in the previous section, most shipowners think of using remanufactured products as a liability within the working system that might cause a total system failure in the case of a breakdown. Milios et al.'s (2019) study also confirms this: “Shipyards stated that some of their customers have specifications to only use new OEM parts and that no reused parts are allowed." The survey in Section 4.2 revealed that 83% of the concerns about RRR products are related to reliability and performance, in contrast to brand-new options.

Hence, the maritime industry's demand for RRR products is still limited. Similar parts are exclusively utilised in sister vessels as spare parts, and some shipowners purchase identical engines from the end-of-life stage to disassemble the machinery and store it as a spare part.

The questionnaire findings also highlighted the critical importance of having the same warranty conditions as a newly manufactured product along with the significance of price advantage and after-sales support for industry acceptance. Legislative incentives such as tax breaks and simplified certification processes would also enhance the perception of circular products. However, there are currently no incentives or structured promotional efforts for remanufactured or reused products within the maritime domain.

Overall, this PhD study has identified five major barriers to the maritime sectors' transition to CE. Overcoming these challenges will be critical for the successful adoption of circular economy practices in the maritime industry. On the other hand, the CE approach brings important opportunities for cost savings, resource efficiency, and environmental sustainability in the maritime sector. The subsequent section will explore opportunities and discuss how advanced circular principles can enhance the effectiveness and resilience of the maritime industry against evolving global challenges.

4.4 Potential Opportunities of CE for the Maritime Industry

4.4.1 Identifying the High-value and High-potential Items Onboard

Commercial cargo and passenger ships, along with naval vessels, are equipped with numerous onboard equipment and components designed for their specific purposes. Equipment onboard vessels varies depending on the ship type and operational objectives. Liquid bulk carriers (tankers) are equipped with pumps for discharging and transferring cargo, whereas general cargo or dry bulk carriers may feature cranes instead of cargo pumps. Or, in some cases, dry bulk carriers are built without any cargo cranes, as they are not intended to visit any ports without cargo loading and discharging facilities that require vessels to possess their own cranes.

This thesis focuses specifically on merchant vessels, including cargo and passenger carriers. On average, all commercial ships have a bridge, superstructure, cargo holds, engine room, and ship hull structure. The bridge includes navigation and radio equipment, internal communication systems, and several alarm systems; the superstructure has accommodation facilities, furniture, and lifesaving and firefighting equipment; the cargo sections may include cargo holds or tanks, cargo pumps, cargo cranes, provision cranes, the container holds depending on the vessel type; engine room consists of a piping system, an engine control room with electrical switchboards, gauges, control panels, workshop machinery such as lathe, drill, welding machine and engine room crane, steering gear, hydraulic pumps and motors, propeller shafts, main and auxiliary engines, air conditioning plant, separators, sewage treatment unit, mechanical ventilation systems, pump systems, air compressors and so on.

Identifying high-value and high-potential items among the numerous pieces of equipment is crucial. By focusing correctly, researchers can demonstrate the significance of advanced circular practices and generate maximum momentum for the industry. In the literature, Bletsas et al. (2017) conducted interviews with maritime stakeholders, screened the items down to 50 pieces of equipment, and carried out an analytical hierarchy process (AHP) to determine which onboard equipment has the highest potential. Table 4-5 below presents the top twelve kinds of equipment based on their findings, where the top two places belong to onboard engines. In line with what was found in Table 4-5, semi-structured interviews with maritime stakeholders for this thesis revealed that engines (main, auxiliary, or emergency) have the most value and recovery potential. Additionally, hydraulic components such as pumps, motors, cylinders, and control groups show significant potential for reuse and remanufacturing despite being ranked seventh. Therefore, this thesis particularly investigated the reuse, remanufacture, and recycling potential of complete engines, main engine parts (engine block, crankshaft, etc.) and components (such as inter/aftercoolers and turbochargers), hydraulic pumps and motors, and hydraulic cylinders and other hydraulic components.

Table 4-5: RRR potential and 2nd hand value of onboard equipment, compiled from Bletsas et al. (2017).

		Potentially applicable EoL Strategy			
#	**On-board Equipment**	**Remanufacture**	**Reuse**	**Recycle**	**2nd hand value**
1	Main and auxiliary engines	Very high	High	Very high to high	High
2	Emergency generators	High	High	High to moderate	High to moderate
3	Airconditioning plant	High	High	High to moderate	Moderate
4	Purifiers (HFO and LO)	High to moderate	High	High to moderate	Moderate
5	Air compressors	High	High to moderate	Moderate	Moderate
6	Deck cranes	High	Moderate	High	Moderate
7	Hydraulic pump and motors	High	Moderate	Moderate to high	Moderate
8	Oil and bilge water separators	Moderate	Moderate	Moderate to low	Moderate
9	Composite boiler	Moderate	Moderate	Moderate	Moderate
10	Windlass equipment	Moderate	Moderate	Moderate	Moderate to low
11	Machine tools (lathe etc)	Moderate	Moderate	Moderate	Moderate to low
12	Engine room crane	Low to moderate	Low to moderate	Moderate	Low to moderate

Referring to Table 4-1 and Table 4-2 it is evident that a complete engine holds the highest market value in use and RRR potential, with hydraulic pumps and motors closely following. Furthermore, engine parts and components like cylinder heads, turbochargers, and engine blocks hold considerable significance, with values ranging from medium to high. In addition to reuse and remanufacture, the questionnaire separately investigated repurposing potential for main engines, auxiliary engines (gen-sets), hydraulic pumps and motors, and cylinders and other hydraulic equipment. The results indicated that auxiliary engines exhibit the greatest potential for repurposing, with hydraulic pumps and motors following closely. Both groups demonstrate medium to high potential for repurposing, as illustrated in Table 4-3.

Overall, due to their highest second-hand market value, reuse and remanufacturing potential, and repurposing potential, complete engines are identified as the most critical onboard equipment for circular practices. This research's stakeholder engagement workshops revealed that auxiliary engines score higher than main engines due to their compact nature and adaptability to other applications beyond their original purpose. Enormously large and heavy, traditional low-speed, two-stroke main engines are less likely to find a new, appropriate application in other industries. In contrast, smaller and more compact auxiliary engines can be exported to, for instance, power generation industries much easier. However, it is known that there are many vessels with smaller and multiple main power units, such as medium- or high-speed, usually four-stroke main engines. Therefore, in such cases, the potential of main engines is higher and should be regarded as the most valuable and potential onboard equipment as well.

The overall strategies for end-of-life engines will be discussed in the following chapters. However, a general overview of how to decide the "fate" of an end-of-life marine engine can be summarised as follows:

A condition assessment should be conducted to determine the fate of an engine when the vessel arrives at a ship repair or recycling facility. Following this initial inspection, the decision on the end-of-life can be made according to the

- Technology,
- Age,
- Overall condition in terms of performance and structural integrity, and
- Regulatory compliance.

If the engine is in good condition, direct reuse can be considered. In this case, regulatory compliance should be checked, as even a 10-year-old engine can be incompliant with the ever-changing regulations in the maritime industry. If the engine complies with the regulations, it can be installed onboard another vessel following recertification and approval from the classification society. If the engine is not compliant or the certification cannot be acquired, the alternative is to use the engine in land-based applications (mainly in factories as generators). If the ship's engine condition is unsatisfactory, repair or remanufacturing options can be considered. In this case, following the disassembly and repair options, regulatory compliance should be checked. In the case of remanufacturing, the approval of the OEM and classification society is critical to using the item on marine applications again. If the condition is particularly poor, the engine is over 25 years old, or the technology is obsolete, scrapping the engine for raw materials remains the only viable solution. The overall process can be visualised in Figure 4-21.

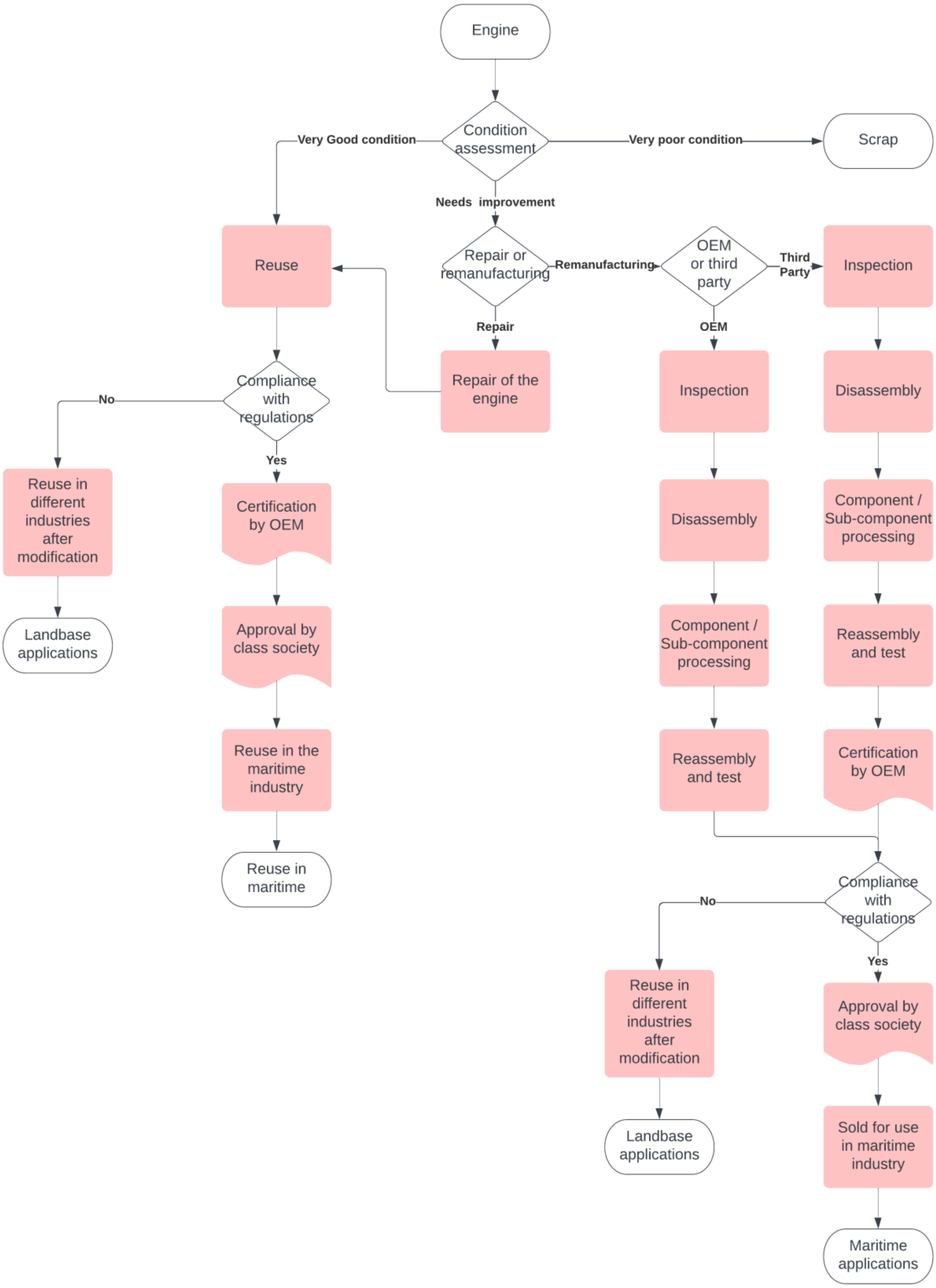


Figure 4-21: End-of-life options for a marine engine (Okumus et al., 2022).

4.4.2 Potential Opportunities of CE principles

Since complete engines were recognised as the most valuable and high-potential equipment in the previous section, the remanufacturing strategy emerges as a pivotal advanced circular solution. Remanufacturing was introduced in Section 2.3, but to briefly recap, remanufacturing is part of end-of-life strategies and is often referred to as the ultimate form of recycling. While recycling often results in the loss of significant amounts of energy and labour (MacArthur, 2013), remanufacturing conserves materials and energy while generating less waste (Karvonen et al., 2015). A recent study by Afrinaldi et al. (2017) demonstrated these benefits through a cylinder block of a diesel engine, confirming 94% reduction in manufacturing energy consumption, approximately 97% material and 57% water consumption savings, along with 90% GHG emission reduction while saving 39% of costs compared to the production of a new cylinder block. Umeda et al. (2012) suggest that high-performance products (e.g., Caterpillar's engines) can be remanufactured for six or even seven cycles, saving enormous energy and material.

The questionnaire results in Section 4.2 showed that maritime stakeholders are not heavily interested in remanufactured parts right now. Still, most of them might change their minds if they are given incentives and their benefits are made clear (see Figure 4-5). Furthermore, when brand-new reliability and quality are assured, 90% of the respondents expressed a potential preference for remanufactured equipment (as indicated in Figure 4-7). The significant capabilities of OEMs and shipyards (in Figure 4-11) and the willingness of equipment manufacturers (in Figure 4-12) further support the possibility of such a future. In addition to that, OEMs are also enthusiastic about potential collaborations in hypothetical remanufacturing hub concepts and even cooperations with 3rd party remanufacturers (referring to Figure 4-13 and Figure 4-14).

The three pillars of sustainability are commonly referred to as the economic, environmental, and social aspects (Murray et al., 2017). And advanced CE approaches, such as remanufacturing, support all these dimensions, leading to a win-win scenario where customers need to pay less for the remanufactured products; OEMs or remanufacturing companies earn more, and the need for raw material and energy consumption is minimised (Jansson, 2016). Table 4-6 below summarises the main benefits derived from circular economy practices. There are many marine engines and other equipment manufacturers in Europe, and increasing remanufacturing rates can help these manufacturers reduce their environmental impact, increase resource efficiency, and enhance their competitiveness in the global market.

Table 4-6: Benefits of remanufacturing, from Okumus et al. (2022).

Stakeholder	Benefits		
Economic (Customers)	The same original performance and reliability at costs typically only 50-80% of a new product.	Better product availability, more options at product acquisition, repair and overhaul times.	
Economic (Businesses)	Remanufacturing is based on an exchange system where customers return cores in exchange for remanufactured products.	Remanufacturing is an additional option to support customers and help lower their acquisition (owning) and maintaining costs.	Profit margins are often bigger for remanufactured products than for new products.
Environment	Reduce manufacturing waste and minimise the need for virgin raw material extraction to produce new products.	Keeping non-renewable resources in circulation for multiple lifetimes.	Reduces manufacturing energy consumption and emissions; resulting in material and energy savings are up to 90%.
Society	Creates new job opportunities for skilled workforce.	Reduced emissions and environmental impact help improve life quality of local residents in the region.	

The realisation of these potential benefits is facilitated by the external and internal processes of remanufacturing. The former corresponds to the acquisition of the core components and sales distribution of the remanufactured products (Karvonen et al., 2015), while the latter corresponds to the operation of remanufacturing within a remanufacturing facility. These processes are shown in Figure 4-22, where the external processes are forward (covering the flow of goods to the customer) and reverse (covering the flow of goods from the customer chain that forms the restorative closed-loop supply chain).

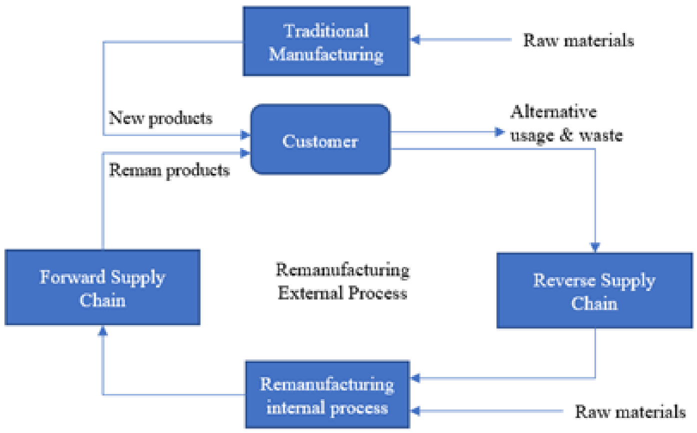


Figure 4-22: External and internal processes of remanufacturing systems, modified from (Okumus et al., 2023b).

The internal remanufacturing process in the figure includes the following steps:

- Inspection
- Disassembly
- Cleaning
- Measuring
- Reprocessing (remanufacture)
- Reassembly
- Testing
- Storage

Depending on an industry's dynamics, stakeholders such as OEMs, their contractors, or independent third parties can carry out the remanufacturing process (Lund, 1984; Sundin et al., 2008). In some cases, a single stakeholder group takes care of all steps, but in other cases, some steps may be subcontracted, such as testing of remanufactured components (Karvonen et al., 2015).

As one of the challenging parts of the remanufacturing operations is collecting the core parts or equipment, the above stakeholders should be adequately supported by supply chain actors. Therefore, logistic operators, warehouses, or businesses that perform core collection, as well as storage facilities, need to be involved. These stakeholders all together form the remanufacturing networks; however, a single leading partner cannot carry out all of the activities, so it is essential to build a network around themselves. Typically, OEMs are the leading parties in this network in the automotive or engineering sector. A similar structure would apply to the maritime industry as well. OEMs remanufacture their products; the logistic partners deliver the core collection in service centres, retailers, trade-ins, and end-of-lease contracts. OEMs usually collaborate with the same partners in the remanufacturing step to integrate it with the usual manufacturing process, called the OEM-centric remanufacturing network. It allows OEMs to ensure quality and customer satisfaction with the remanufactured or manufactured items (Karvonen et al., 2015). Another alternative is the sub-form of the OEM-centric remanufacturing network. A contracted company conducts the remanufacturing operation (internal process), while the OEM is still in a controlling role. In the third option, the OEM is less (or not at all) involved directly in the case of independent third-party remanufacturers, and in this case, the third party collects the core, remanufactures it, and sells remanufactured products. They might also choose to subcontract some steps, which hints at a collaboration requirement in this model. This model works in a more industry-specific form, requiring basic products or markets with a high circulation of goods. Due to the extremely high standards and quality assurance demands of the marine environment, implementing this model poses challenges. Therefore, OEM-centric or OEM-controlled contractor options might be more suitable for the maritime industry, as they provide more control over the remanufacturing process and ensure compliance with industry standards. Additionally, these options can offer the highest quality assurance and warranty support for customers in the maritime sector.

Ultimately, regardless of the process model chosen, the benefits of remanufacturing remain clear. Remanufactured products can offer equal value to new products with even better reliability than the brand-new alternatives (Wahab et al., 2018). From an environmental perspective, remanufacturing contributes to sustainability, energy, and material savings while reducing waste and emissions (Gong et al., 2022; Peng et al., 2019; Wang et al., 2021). As discussed in Section 2.3, the maritime industry exhibits a remanufacturing intensity of only 0.3%, in contrast to the aviation industry's leading position at 11.5%. The remanufacturing turnovers in the aviation, automotive, rail, and maritime sectors amount to €12.4bn, €7.4bn, €0.3bn, and €0.2bn, respectively. The number of cores remanufactured in maritime is just a fraction of that in other transportation industries. Even in such dire circumstances, the maritime industry saved 15,000 tonnes of material and mitigated 40,000 tonnes of CO_2-equivalent emissions through remanufacturing in Europe (Wahab et al., 2018). Hence, significant opportunities await the maritime industry as it enhances and expands its remanufacturing capabilities to align with those of other transportation sectors. Such advancements could not only enhance cost savings and environmental benefits but also foster a more sustainable future for the maritime industry.

4.5 Maritime Circularity Framework

This section introduces a comprehensive maritime circularity framework derived from the findings of this chapter and the literature review in Chapter 2. The framework is structured around three main pillars, represented metaphorically as the legs of a three-legged stool. Each leg is indispensable for achieving sustainable success in the circularity transition, as illustrated in Figure 4-23. The framework addresses the barriers and opportunities identified earlier in this chapter and provides a foundation for the research described in Chapters 5, 6, and 7.

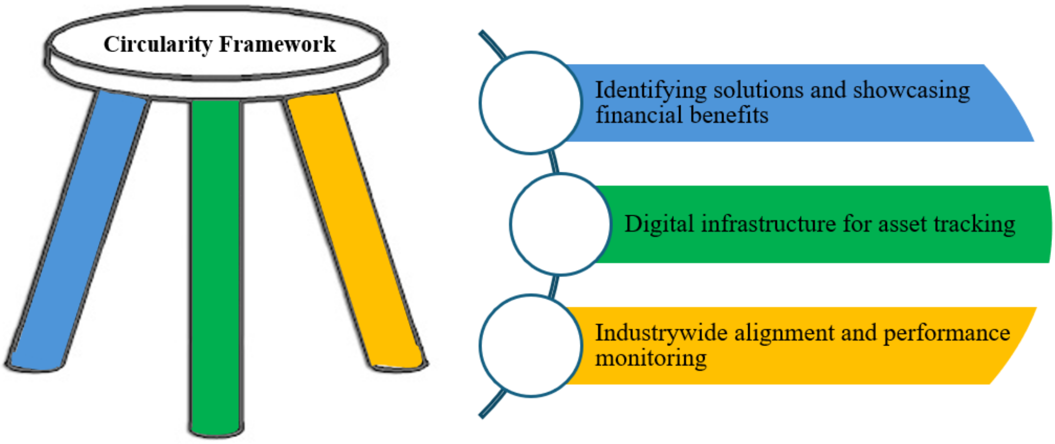


Figure 4-23: Three-legged stool showing the developed circularity framework.

4.5.1 Key Propositions Guiding the Maritime Circularity Framework

The framework is built upon the following propositions, emerging from the findings of Chapter 4 and guiding the three pillars:

1. **Technology and Strategy Solutions:** Overcoming regulatory, technical, and logistical barriers requires innovative solutions tailored to the unique challenges of maritime stakeholders. These solutions must demonstrate economic and environmental benefits to gain widespread acceptance in the industry.

2. **Digital Infrastructure:** A dedicated digital infrastructure is essential to enable effective tracking, monitoring, and lifecycle management of maritime assets, thereby addressing the lack of reverse supply chain visibility and data availability for circular practices.

3. **Stakeholder Alignment through Metrics:** Circularity metrics tailored to different maritime stakeholder groups can drive collaboration, enable accountability, and foster continuous improvement towards circularity. These metrics must address sustainability dimensions comprehensively while allowing stakeholders to benchmark performance and identify areas for enhancement.

These key propositions, derived from Chapter 4 findings, form the foundation for the three pillars of the maritime circularity framework: Technology and Strategy Solutions, Digital Infrastructure for Maritime Assets, and Stakeholder Alignment through circularity metrics.

4.5.2 Three Pillars of the Maritime Circularity Framework

- Pillar 1: Technology and Strategy Solutions

The first pillar focuses on identifying and implementing strategic and technological solutions that enable circularity in the maritime sector. This pillar directly addresses barriers such as low awareness of circular economy practices, lack of trust in remanufactured products, and limited access to documented case studies. To bridge these gaps, Chapter 5 investigates a diverse set of strategies and technologies, including transformative business models, digital tools, and smart recovery decision-making systems.

The chapter includes a marine engine remanufacturing case study to provide empirical evidence of the financial and operational benefits of circular practices. This study documents the remanufacturing process of an end-of-life engine, compares its performance with a new engine, and presents a cost-benefit analysis. These findings demonstrate the feasibility and value of circular practices, particularly for original equipment manufacturers, and underscore their potential for industry-wide application.

- Pillar 2: Digital Infrastructure for Maritime Assets - Facilitating Asset Tracking and Lifecycle Management

The second pillar addresses the significant gap in digital infrastructure needed to support circular practices. Chapter 6 introduces a maritime asset tracking system and a dedicated database structure to enhance asset tracking, core collection, and value retention in the maritime sector. This pillar responds to the challenges identified in Chapter 4, such as limited data availability and inefficient core collection processes.

The chapter provides a detailed description of the MAT system, including database architecture, interface forms, and example queries. A case study highlights the system's potential benefits by showcasing the enhanced end-of-life value of a sample vessel in a circular scenario. This pillar emphasises the transformative impact of digitalisation in bridging gaps between current practices and advanced circular economy principles.

- Pillar 3: Stakeholder Alignment through Circularity Metrics - Enhancing Collaboration and Accountability

The third pillar focuses on aligning maritime stakeholders through the development of tailored circularity metrics. Chapter 7 presents 59 metrics tailored for nine stakeholder groups to support Stakeholder Alignment through Circularity Metrics in Pillar 3. These metrics are validated through stakeholder workshops and linked to five sustainability aspects: financial, supply chain, raw material consumption, waste and emissions, and social impact.

A case study on ship repair yards demonstrates the practical application of these metrics. Three shipyards were evaluated and benchmarked based on their operations, providing actionable insights to enhance circularity performance. This pillar highlights the importance of data-driven decision-making and accountability in driving the maritime industry's transition to circularity.

All in all, the three pillars of the framework which comprises Phase II of this PhD study are deeply rooted in the findings of Chapter 4:

- **Barriers and Opportunities Identified in Chapter 4:** The framework addresses low awareness, lack of reverse supply chain infrastructure, and negative perceptions of circular products through targeted solutions in each pillar.

- **Stakeholder Engagement:** Insights from stakeholder surveys and workshops underpin the development of strategies, digital tools, and metrics, ensuring relevance and practicality.

- **Path to Circularity:** By linking the barriers and opportunities in Chapter 4 with actionable solutions in Chapters 5, 6, and 7, the framework provides a structured roadmap for the maritime industry's circularity transition.

4.6 Chapter Summary

This chapter summarised the barriers to CE in the maritime industry as well as identifying potential opportunities for implementing circular economy principles in the sector. The survey results and the literature were combined together to better understand the nature of the obstacles to maritime's circular transition. Marine engines were identified as having the highest value and potential among onboard equipment on merchant vessels, making them the most strategic target for capitalising on the benefits of advanced circularity within the maritime industry.

5 Technology and Strategy Solutions for a Circular Maritime Industry

5.1 Chapter Overview

This chapter is the first leg of the maritime circularity framework in the Phase II of this PhD research. It addresses a significant gap in the literature by exploring strategy, technology, and hardware solutions to facilitate CE transformation within the maritime industry. Furthermore, this chapter offers an in-depth overview of CE practices among marine engine OEMs. It is followed by a thorough case study demonstrating the benefits of remanufacturing a marine engine from a high-speed passenger ferry. This chapter has been partly published in the Journal of Cleaner Production (2023) volume 382 as follows:

Okumus, D.; Gunbeyaz, S.A.; Kurt, R.E.; Turan, O. Towards a circular maritime industry: Identifying strategy and technology solutions. *Journal of Cleaner Production* **2023**, *382,* 134935. https://doi.org/10.1016/j.jclepro.2022.134935

5.2 Strategic Solutions

5.2.1 Closed-loop Supply Chains (CLSC) and Recovery Hubs

CLSCs should be established to ensure restorative circular economy principles in any industry that provides physical products. In the simplest terms, materials flow unidirectionally through traditional forward supply chains, from raw material suppliers to producers, distributors, retailers, and consumers. However, in CLSCs, used parts, components, or equipment are returned to manufacturers via reverse flows (Souza, 2013).

CLSCs have several more complicated characteristics compared to traditional forward supply chains (Han et al., 2017). First, the input of the remanufacturing process, which is the used product returns, is uncertain in terms of quality, quantity, and arrival time. Moreover, the elements of the core return side of the chain may differ from the forward distribution network. Secondly, due to the nature of the concept, returned products of different conditions will need different remanufacturing processes, resulting in extra time, cost, and capacity usage (Souza, 2014). Some returned products may not be suitable for remanufacturing, necessitating separate recycling processes. According to Guide and Van Wassenhove (2002), some everyday activities linked to product recovery in the reverse chain include end-of-use or end-of-life product acquisition, reverse logistics, used product checks (testing and grading), remanufacturing, and remarketing. In order to establish reuse-remanufacture-repurpose principles in the maritime industry, maritime OEMs should pay particular attention to used product acquisition and logistics, from ship recycling yards to remanufacturing centres.

Expanding on the CLSC concept, the focus now turns to product recovery hubs. Unlike conventional forward supply chains, where facility location models provide the optimal configuration for the chain, such as the optimum number, location, and size of warehouses that minimise distribution and fixed costs, in CLSC, the firm also needs to locate consolidation centres or hubs for returns and recovery facilities for remanufacturing, recycling, or scrap disposal. Ideally, consolidation centres or hubs round-up returns from numerous sources, test them and route them to recovery facilities (Souza, 2013). In the context of the circular economy, remanufacturing hubs serve as important enablers for achieving environmental goals such as minimising waste, conserving resources, and lowering the overall environmental impact of manufacturing processes (Singhal et al., 2019). By focusing on activities like dismantling, cleaning, refurbishing, and testing products, these hubs facilitate the transformation of used items into functional goods, aligning with the principles of a closed-loop supply chain (Gaspari et al., 2017).

Figure 5-1 illustrates a general process flow for closed-loop supply chain activities. Remanufacturers should analyse and consider what level of reuse is appropriate, which often entails a quality grading system for returned parts or components. Research indicates that product design and built-in quality during new production directly impact the potential recoverable value at the end-of-use or end-of-life of a product (Radhi & Zhang, 2016). Therefore, OEMs aiming to achieve design for remanufacturing principles are often in the best position to extract future value from the product (Akturk et al., 2017). In the maritime industry, specific stakeholders are closely related to the processes shown in Figure 5-1. In fact, traditionally, products such as engines are purchased by ship owners, often with the guidance of design offices and/or shipyards, and then, around the end-of-use period, the ship may be sold to a recycler instead of another operating owner. Therefore, ship recycling facilities are often involved as vessel owners at the end-of-use stage, which makes them a critical stakeholder group for maritime CLSCs.

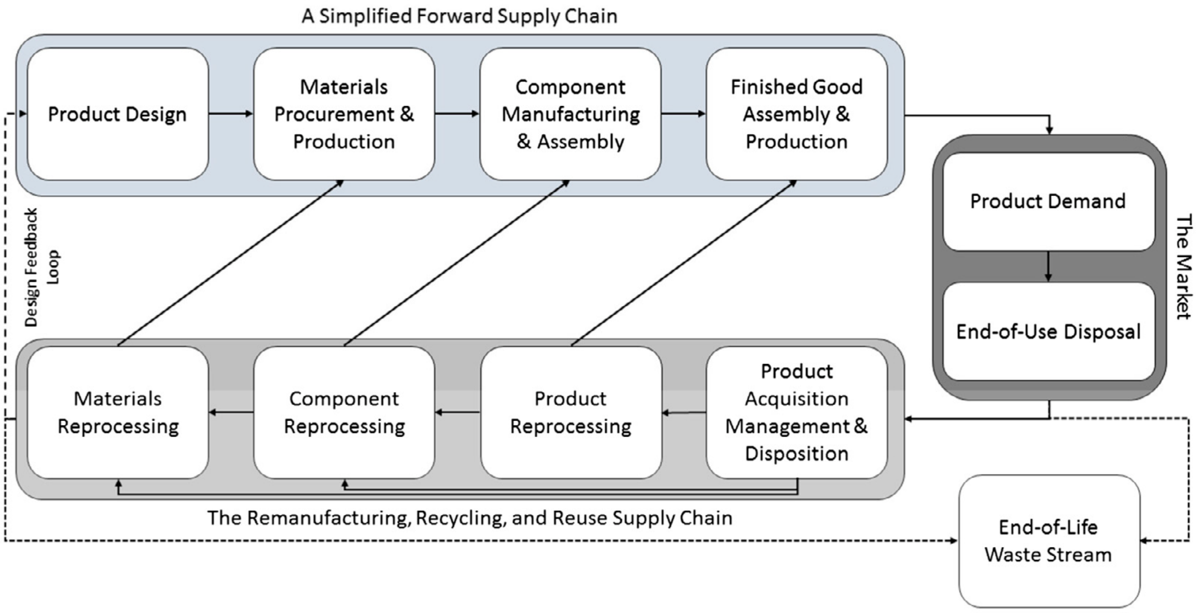


Figure 5-1: A process flow perspective of closed-loop supply chain activities (Abbey & Guide, 2018).

5.2.2 Seeding Strategies

A certain level of core parts inventory is essential for a successful start to remanufacturing production. In this context, seeding strategies might help the OEMs by accelerating the core part collection phase. Seeding involves selling a specific number of new components or parts as remanufactured products to gather used parts and achieve the desired core inventory level to start remanufacturing operations. The quantity of new products released is called the seed stock (Akçali & Morse, 2004).

With a higher volume of seeding stock, it becomes feasible to recover more core components through the reverse supply chain over the planning horizon. Consequently, remanufacturing OEMs can procure the necessary number of cores to enhance the efficiency of remanufacturing operations earlier (Abbey et al., 2018).

Many durable goods industries, such as automotive, power generation, and heavy equipment, implement seeding since the lack of cores disrupts their remanufacturing operations. Abbey et al. (2018) highlighted that managers from companies such as Caterpillar, Cummins, and Delco Remy view the seeding strategy as a valuable tool to achieve economies of scale sooner in manufacturing and remanufacturing operations. Their research discovered in the diesel engine industry that seeding has the potential to boost total profit from remanufacturing by up to 40% in optimal conditions and approximately 23% on average. Therefore, despite potential losses from selling seeded units, seeding can significantly boost the company's overall profits by enabling the earlier availability of remanufacturing operations (Abbey et al., 2018).

Some OEMs in the maritime industry are already applying seeding strategies. This research encourages other OEMs in the industry to carry out initial studies for potential seeding strategies in their field. Most of the components in the engine room of a conventional merchant ship or a pleasure craft are remanufacturable and, therefore, good candidates for seeding strategies.

5.2.3 Take-back Strategies: Trade-ins & Leasing

Guide and Van Wassenhove’s study in 2001 was one of the pioneers who introduced the idea of product acquisition management, where an OEM can control the timing, quantity, and quality of product returns through appropriate economic incentives to increase the profitability of recovery activities (Guide & Van Wassenhove, 2001; Souza, 2013). Presently, trade-in policies provide customers with trade-in value, such as discounts or credits, for their used products during a purchase, regardless of whether they are new or remanufactured. That way, while customers put their old equipment to good use, the OEMs trigger their reverse supply chain first-hand.

Trade-in practices are gaining popularity and are on the verge of becoming the norm, particularly in saturated and high-technology sectors (Tozanli et al., 2020b). Considering the world merchant fleet's average growth rates, which are 3.3% in DWT and 1.8% in the number of ships (over 1000 GT) from 2016 to 2021 (Infomaritime EU, 2021), one might conclude that the market is saturated. Numerous global OEMs in the maritime sector are knowledgeable about trade-in policies, some with successful implementations; for instance, Cummins executes trade-in strategies effectively. After purchasing a Cummins product, customers receive a discount if they return their old components or parts. The returned cores are shipped from dealers to Cummins' used product depot, and when they arrive, customers are given credit for returning the core components (Souza, 2013). Cummins is not the only company implementing such strategies. Other OEMs, such as Caterpillar, Volvo Penta, and so on, also execute similar strategies. Apart from that, there are different approaches for determining optimum trade-in discount rates; some calculate the trade-in value proportional to the used product's age, while others offer a standard tariff. In general, Souza (2013) points out that remanufactured engines and engine parts are sold at around a 35% discount compared to new alternatives.

Another potentially attractive solution for maritime stakeholders is leasing. Leasing enables OEMs to acquire used cores for remanufacturing while controlling the used/second-hand market. With a standard leasing offer, OEM always gets the used products and remanufactures, as long as product durability and environmental factors allow. In contrast, in the case of traditional selling, end-users (ship owners or operators) or recyclers sell used products in the second-hand market (Souza, 2013). On the other hand, from the customers' perspective, the most crucial advantage of leasing is replacing high product costs with instalment plans over the lease term, thus easing the financial load on customers and facilitating better cash flow management. The following section will explain a more advanced version of leasing solutions under Product Service Solutions.

In addition to trade-in and leasing approaches, OEMs can impact the resale value of products in the secondary market by imposing a compulsory relicensing fee on products remanufactured by third-party firms (Oraiopoulos et al., 2012).

Consequently, relicensing expenses can efficiently regulate the scale of both third-party and OEM remanufacturing activities. Relicensing fees are essential, especially when third-party remanufactured options challenge new and OEM remanufactured products. Moreover, the quality of a remanufactured product, even when done by a third-party remanufacturer, remains contingent on the quality of the original new product by OEMs.

5.2.4 Product Service Systems (PSS)

PSS offers many advantages for the manufacturer, service provider, and end user. According to (Kerin & Pham, 2020), PSS is a distinctive business model that mainly supports high-quality, durable, and long-lasting products. In product service solution systems, the ownership of the product belongs to the OEM, and it is leased to the user. The payment is based on the fulfilment rate of the customers' operational requirements by providing services to them. This is possible thanks to the shift in the producers' focus from selling products to fulfilling needs (Chierici & Copani, 2016). Therefore, PSS lets the manufacturer "squeeze value out of the product for as long as it is economically viable, utilising repair and service strategies to achieve multiple life cycles," which also benefits the remanufacturing operations by providing both steady supplies of core components and demand for remanufactured equipment (Kerin & Pham, 2020).

To adapt PSS successfully, OEMs need to modify their organisation and promote "servitisation" for sound and well-organised service delivery. In return, PSS influences both the demand and opportunities for remanufactured parts and products; present studies on circular businesses revealed that PSS-driven and remanufacturing-based business models are widespread archetypes (Rosa et al., 2019).

When relevant technology solutions are coupled with the PSS strategy, the OEM can closely monitor product usage patterns, allowing it to step in and take necessary actions when needed to ensure maximum utilisation and product life. Because of its suitability with advanced technology solutions, which will be covered in the coming sections, PSS is an exceedingly effective strategy for the maritime industry. As the equipment inspection at any time becomes relatively more straightforward, and OEMs are more effective in deciding the recovery time and options for end-of-life equipment, PSS also paves the way for remanufacturing to become the main route at the end-of-life period (Fofou et al., 2021). In addition to these benefits, when it is combined with appropriate technology solutions, PSS can form a basis for predictive remanufacturing as well (Khan et al., 2018), that is, simply estimating possible future defects in the product and carrying out remanufacturing operations at the optimum time, resulting in lower remanufacturing costs and higher utilisation rates. In this case, concepts such as product availability, up-time, or other performance metrics can become the foundation of the agreement between the service provider or OEM and the end-user or customer. Moreover, the proper combination of PSS and Industry 4.0 applications, primarily the Internet of Things, can enable pay-per-use or pay-per-performance systems (Bressanelli et al., 2017). For instance, this might lead to a future scenario where marine engine OEMs charge for a certain amount of engine working hours or nautical miles travelled instead of conventional engine sales or leasing agreements.

High-technology products like diesel engines in marine or other machinery industries come with electronic control units, numerous sensors, and other hardware. In the sales phase, they are almost always combined with preventive maintenance services, so the foundation already exists. For example, a business-to-business remanufacturing pioneer, Caterpillar, sets a good standard for providing PSS-like solutions in the power generation industry. The firm offers various service options to meet changing customer needs, including rebuild programmes based on product performance (Copani & Behnam, 2020).

5.3 Technology Solutions

This section will cover software-focused solutions. It should be noted that almost all of these solutions depend on inputs from numerous pieces of hardware equipment; therefore, it is advised to consider them complementary.

5.3.1 Industry 4.0

Industry 4.0 is the fourth stage of industrialisation to achieve high degrees of automation in production via the widespread use of information and communication technologies (Yang et al., 2018). Industry 4.0 encompasses various technological concepts, including machine connectivity, big data analytics, artificial intelligence (AI), blockchains, smart factories with autonomous robots, additive manufacturing, virtual reality (VR), and augmented reality (AR) (Kerin & Pham, 2019; Tozanli et al., 2020b). It covers facilitating data capture and exchange throughout various stages of the supply chain, as well as accelerating the use of smart remanufacturing operations (Fofou et al., 2021). Combining these innovative technologies is essential to create original, reliable, sustainable, agile, flexible, responsive, knowledge-based, and customer-oriented solutions in high-technology sectors. From the I4.0 standpoint, the hybrid use of blockchain and the Internet of Things (IoT) is inseparably linked to the vision of future manufacturing, shipping, and product recovery procedures (Tozanli et al., 2020b). Technological advancements under the I4.0 umbrella can be inserted into the final products and/or the equipment used in the remanufacturing process to optimise end-of-life decision-making for remanufacturing-candidate products.

I4.0’s primary notion is to expand the availability and holistic use of meaningful data by networking all assets, resources, and organisations engaged in the value chain to generate more value from accessible data and maximise consumer benefit (Yang et al., 2018).

Controlling the timing, quality, and quantity of returned cores remains a significant challenge for remanufacturers, as discussed in earlier sections of this study. At this point, the smart services concept is associated with technological solutions that enable advanced and disruptive product-service systems. As mentioned in the strategic solutions section, technological advancements within the I4.0 umbrella can significantly support the PSS strategy. In an advanced PSS business model, which offers a pay-per-performance concept, OEMs or dealers/retailers maintain ownership of the product and only provide the service or use to consumers (e.g., selling "engine flying hours" rather than "engines"). As a result, the system requires proper product monitoring features throughout the operation and anticipation for remanufacturing processes on returned cores based on the product's estimated remaining life. On the other hand, since buyers pay for the service rather than the product, it enhances market acceptance of remanufactured items, leading to a successful remanufacturing model.

Predictive maintenance might be made possible by the early identification of faults by real-time monitoring of products in use and data analysis using embedded sensor networks and cloud computing. As a result of I4.0, the increased connection between products, consumers, and producers creates enormous potential for enhancing the product service model (Yang et al., 2018).

For example, certain OEMs lease fully equipped engines to power plants that demand maximum equipment availability in the power generation industry. The engines are embedded with smart sensors, and the OEMs constantly monitor crucial parameters such as temperature, pressure, consumption, vibration, etc. Sensor data is collected and stored on a central server via a network to predict wear, estimate the usable life of components, and schedule timely repairs or remanufacturing (Yang et al., 2018). All in all, I4.0's primary benefit is its capacity to generate and access real-time information, enabling enhanced visibility and risk mitigation across the supply chain network (Fofou et al., 2021). The applications of Industry 4.0 mentioned have the potential to deliver value to stakeholders in the maritime industry, including OEMs, ship owners/operators, shipyards, and ship recyclers.

5.3.2 Internet of Things (IoT)

With a simple definition, IoT refers to numerous physical devices that collect and share data. The IoT is driven by small, widely dispersed, and practically linked ubiquitous sensors that aim to continuously monitor individual objects and overall systems throughout their operational lifespan (Tozanli et al., 2020b). From the CE aspect, IoT offers significant advantages, enabling remanufacturers to analyse used cores, connect the physical conditions of assets with sensor data, and ultimately make more precise remanufacturing decisions based on usage data. This enhancement will also boost the efficiency of remanufacturing operations.

Typically, determining the optimal time for remanufacturing involves monitoring the performance or physical and structural integrity of "key components" over time to identify the most suitable moment for product remanufacturing (Fofou et al., 2021). Expanding on this, a product consists of various components, with certain ones identified as "key components" due to their critical role in the overall product. Through digital monitoring of these crucial components, smart systems can predict the optimal timing for remanufacturing. Leading the way in remanufacturing, companies like Caterpillar have been promoting their condition monitoring services to control equipment expenses, improve product performance and utilisation, and mitigate component failure risks (Caterpillar, n.d.-c).

5.3.3 Big Data Analytics and Artificial Intelligence (AI)

Big data analytics is the application of sophisticated analytical methods to extensive, diversified data sets whose size or type exceeds the capacity of typical conventional databases to gather, manage, and analyse the data promptly. Big data is characterised by its substantial volume, high velocity of change, or extensive diversity. Artificial intelligence (AI), mobile and social relationships, and the IoT are increasing data complexity through new data formats and sources. For instance, big data is generated in real-time and at a large scale by sensors, devices, video/audio sources, networks, log files, transactional applications, the web, and social media (IBM, 2024).

In the context of the circular economy, integrating reverse logistics, cloud-based systems, and the Internet of Things (IoT) allows for the accurate interpretation of end-of-life decisions using big data via AI and machine learning (ML) algorithms. Chapter 6 will explore this subject further and propose an in-depth database solution for establishing a digital infrastructure within the maritime sector.

5.3.4 Digital Twins (DT)

Digital twinning is a method for defining and modelling a physical item's properties, characteristics, components, and performance using advanced digital tools (Schroeder et al., 2016). The virtual representations of tangible items are enabled using data collected through IoT infrastructure and data-management hardware such as sensors and RFID tags implanted in their physical equivalents (Tozanli et al., 2020a). Once invested in equipment, IoT sensors monitor and collect data about essential components and parameters, such as consumption levels, run cycles, and malfunctions. Additionally, DT models include all relevant product information, including serial numbers, model names, production dates, bills of materials, and assembly and disassembly instructions (Alqahtani et al., 2019). Therefore, digital twins might provide precise data on products' behaviour, including performance and functionality, at the product and component levels (Chen & Huang, 2021; Miller et al., 2018; Tozanli et al., 2020a).

By almost removing uncertainty about the state of returned end-of-life cores, digital twins may play a crucial role in supporting rapid decision-making and planning in used component acquisition. OEMs may use predictive twins to estimate the remaining usable life of items based on data received via IoT infrastructure for product and component functionality. Predictive twins imitate the behaviour of assets or systems using historical data from their simulated real-time occurrences. The remaining service life of a product may be estimated using previous data collected from the product and its components, from other comparable devices, or a combination of these. Manufacturers may use this prediction model to forecast the future conditions of the full product and parts before proposing trade-in prices or offering remanufacturing services (Tozanli et al., 2020a). Figure 5-2 illustrates IoT and data analytics as crucial components of digital twins and summarises the potential advantages of DTs in remanufacturing, which maritime OEMs can also use. Besides OEMs, engineering consultancy firms, shipyards, or turn-key solution providers might consider generating the digital twin of a desired ship’s engine room to maximise the utilisation of machinery and equipment there. By doing so, asset tracking would substantially increase, meaning improved circularity metrics and remanufacturing opportunities.

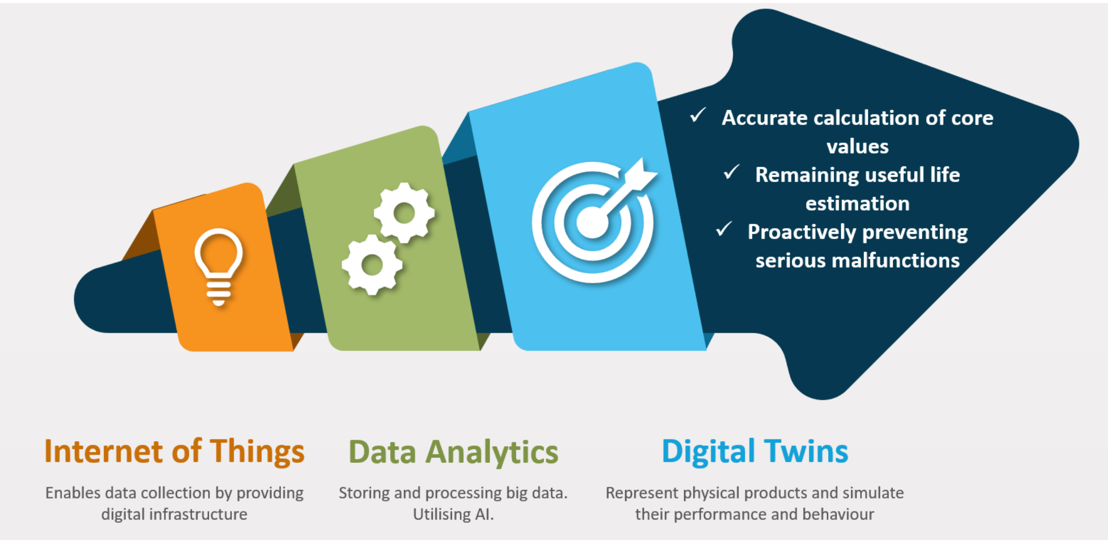


Figure 5-2: Foundations and benefits of digital twins.

5.3.5 Database and Blockchain

Typically, a database management system (DBMS) is in charge of managing a database. Together, the data, the DBMS, and the programmes that run on them are regarded as a database system, simplified as a database (ORACLE, 2020). To make processing and data querying as efficient as possible, data in today's most prevalent forms of databases is often structured in rows and columns in a sequence of tables. Thus, data may be easily accessed, managed, altered, updated, controlled, and organised. Databases commonly use the Structured Query Language (SQL) for writing and querying data (ORACLE, 2020). If the system is complex and generates large amounts of potentially live and diverse data, it is classified in the big data category.

Blockchain technology enables secure data transmission to digital twins. It is a decentralised peer-to-peer ledger that encrypts each transaction to assure its security and permanence (Yadav & Singh, 2020). This functionality enables data to be safely kept in a decentralised framework under cryptographic monitoring, allowing digital twins to securely transmit data from IoT devices (Tozanli et al., 2020a).

5.3.6 Smart Recovery Decision-Making Systems (SRDM)

Smart recovery decision-making is essentially concerned with making a recovery decision with a combination of smart solutions. In other words, according to SRDM systems, a product may be removed from operation and sent to the recovery process at any phase of its lifespan by using decision-making algorithms that optimise efficiency. SRDM leverages advanced technologies such as artificial intelligence, the internet of things, big data, and machine vision—image-based inspections—to identify products that should be withdrawn from the supply chain for repair, refurbishment, remanufacturing, or recycling. Remanufacturing and repair are often the most preferred options. SRDM systems depend on data-collecting devices that communicate product parameters and decision-making algorithms to put everything together.

Today's technological developments make more advanced solutions applicable, provided that all stakeholders are dedicated and cooperate.

In a perfect scenario, the stakeholders in the maritime industry would benefit from:

- Continuously reporting smart on-board components equipped with sensors (IoT),
- Big Data analytics, analysing the vast amount of information gathered by IoT (Big Data),
- Blockchain technology to ensure higher database safety (BC),
- Digital Twins replicating both the vessel and onboard components' characteristics, enabling what-if experimental scenarios for maritime assets (DT).
- Accurate EoL time and decommissioning value estimation for all marine assets by ML algorithms (AI),
- Component route estimation for EoL products by ML– i.e., whether to reuse, remanufacture, or recycle as scrap (AI), and
- Accurate second-hand value estimation by ML for a vessel or single component at any time (AI).

These technological solutions would pave the way for:

- Maximised EoL utilisation,
- Optimised reverse supply chain performance, and
- Higher circularity and sustainability rates due to maximised remanufacturing, in the maritime domain.

5.4 Hardware Technologies

This section covers complementary hardware solutions to assist strategy and technology solutions.

5.4.1 Smart Sensors

Sensors, in general, are tools that detect and react to changes in their surroundings. Inputs may include light, temperature, motion, and pressure. Sensors provide useful data, which they may communicate with other connected devices or management systems through protocols (such as MQTT or HTTP) if they are linked to a network.

Smart sensor types include wireless communication technologies (e.g., Bluetooth for short-range communication, Wi-Fi for high-speed data transfer, ZigBee for low-power applications, etc.) essential for communication and data exchange in IoT systems. Smart sensors in the IoT play a pivotal role in collecting, processing, and intelligently transmitting data, thereby aiding in the automation and optimisation of processes in smart environments. These sensors are integrated into devices and nodes to enable communication without human intervention (Sehrawat & Gill, 2020).

In the manufacturing industry, sensor functionalities are crucial for enhancing operational efficiency, ensuring product quality, and enabling predictive maintenance. Various types of sensors, such as temperature sensors, pressure sensors, humidity sensors, vibration sensors, and proximity sensors, are commonly used in smart manufacturing processes to monitor and control different parameters (Frantlović et al., 2016; Kalsoom et al., 2020; Soltani et al., 2020). Integrating these sensors into smart manufacturing systems enables real-time monitoring, data collection, and analysis to optimise production processes, reduce downtime, and enhance overall productivity. By utilising sensor data, manufacturers can implement predictive maintenance strategies, improve quality control, and achieve operational excellence in the Industry 4.0 era.

5.4.2 Radio Frequency Identification (RFID)

RFID is a wireless technology that consists of two parts: tags and readers. The reader transmits radio waves and receives signals from the RFID tag through its antennas. Tags, which convey their identity and other data to adjacent readers through radio waves, may be active or passive. These tags are powered by the reader and don't have a battery, so they don't need to be recharged. Batteries power active RFID tags (US FDA, 2018). RFID tags can store a variety of data, ranging from a single serial number to many pages of information. Readers may be portable and transported by hand, or they might be placed on a post or suspended from the ceiling (US FDA, 2018).

RFID can be integrated with IoT applications to increase transparency at individual product or component levels, resulting in more precise life-cycle monitoring (Meng et al., 2016). RFID and IoT combinations also allow for keeping track of core part movement in a reverse supply chain. There are various examples of movement tracking in numerous industries, including engine manufacturers (Kerin & Pham, 2019).

5.4.3 Quick Response Codes (QR)

The Quick Response (QR) codes are the advanced version of standard one-dimensional barcodes. Unlike one-dimensional barcodes that store only horizontal data, QR codes can store information in two dimensions, both horizontally and vertically. Therefore, QR codes have significantly higher information capacity than barcodes and better fault tolerance. The quick recognition across various devices and cost-effectiveness make QR codes appealing for industrial use due to their efficiency and affordability (US FDA, 2018).

Due to the increasing use of smartphones and mobile devices, QR codes have become an entrance to the IoT, with properties such as quick and easy reading, the ability to store much more data than traditional codes, and flexibility associated with swift and straightforward access to information. There is recent research regarding next-generation QR codes called luminescence QR codes, which significantly increase the information capacity of standard QR codes while adding temperature-sensing features (Ramalho et al., 2019).

5.5 Current Practices Regarding CE Amongst Well-known Marine Engine Manufacturers - OEMs

Many well-known OEMs in the maritime industry address circular economy subtopics in their after-sales services. This thesis has investigated the circular options provided by some mainstream marine engine manufacturers, such as Wärtsila, Caterpillar, Volvo Penta, MTU, and Cummins. Then it briefly mentions third-party reconditioners.

5.5.1 Wärtsilä

Wärtsilä applies a CE approach in the maritime sector by managing the lifecycle of its products through careful design, supplier selection, production methods, and optimising transportation, maintenance, and repairs. The company recognises that green fuels alone will not make shipping sustainable, highlights that increasing the industry's circularity is critical, and points out the lack of a standardised set of metrics to track progress (Faye & Butcher, 2023).

Wärtsilä's focus on CE principles aligns with the growing emphasis on sustainability in the maritime industry. By reconditioning products and components, they extend their reliable service life and improve operational performance. Wärtsila carries out maintenance and repairs, applies product upgrades and modifications, and reconditions two- and four-stroke engines, as well as other components, in more than 70 workshops worldwide (Wärtsilä, 2022). In addition, Wärtsila can carry out the complete remanufacturing of two-stroke marine engines in seven Remanufacturing Centres worldwide within their 2-Stroke Remanufacturing Solutions programme (Wärtsilä, 2012).

The company says they "bring used and worn-out components back to their full functionality" while restoring them to their original component specifications and ensuring full service life (Wärtsilä, 2012). Figure 5-3 below illustrates an example of a restored part by Wärtsilä. The benefits of remanufacturing are elaborated as significant cost reductions through the reuse of core components, high reliability, adherence to original OEM quality standards, incorporation of the latest modifications, and minimised environmental impact.

Figure 5-3: Wärtsilä parts remanufacturing example (Wärtsilä, 2012).

Wärtsila states that the remanufacturing process is essentially carried out on the customers' engines and components, ensuring that customers receive their assets back. Additionally, they have established an exchange option where they offer specific remanufactured components and parts readily available from their stocks, allowing customers to enjoy the benefits of remanufacturing without experiencing lengthy lead times. Some examples of potential remanufacturing savings can be listed as follows:

- Remanufacturing cylinder covers: savings of up to 75%,
- Remanufacturing piston crown: savings of up to 50%,
- Remanufacturing piston rods: savings of up to 50%,
- Remanufacturing valve spindles: savings of up to 70%,
- Remanufacturing (instant exchange available) injection control units: savings of up to 50%,

- Remanufacturing (instant exchange available) fuel pumps: savings of up to 65%,
- Remanufacturing (instant exchange available) servo oil pumps: savings of up to 50%.
- Remanufacturing (instant exchange available) pressure control valves: savings of up to 40% (Wärtsilä, 2012).

Wartsila exchange stock warehouses are located in the Netherlands and Singapore, and Figure 5-4 below depicts their global service network and remanufacturing centres.

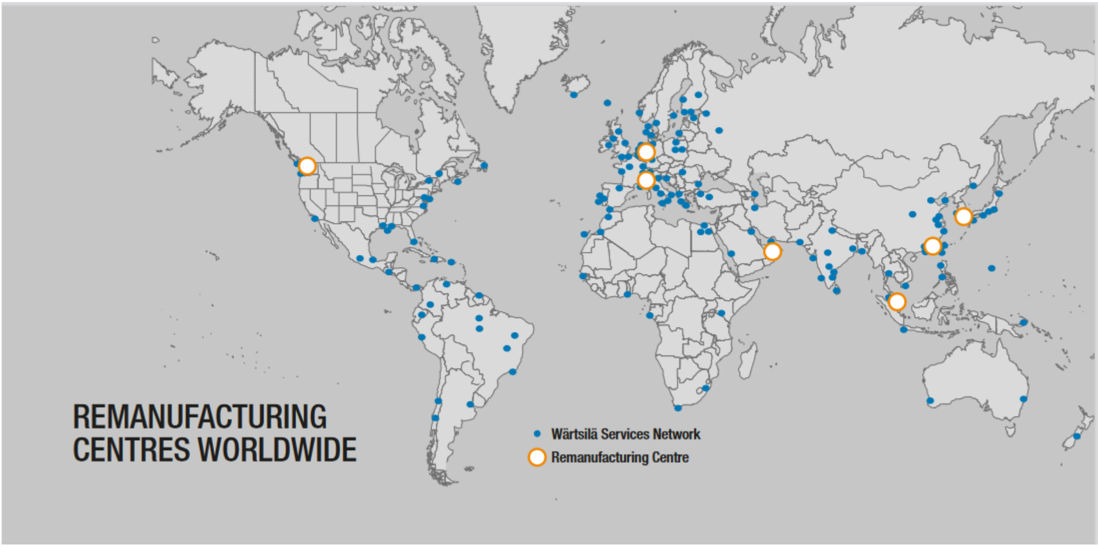


Figure 5-4: Wärtsilä service network and remanufacturing centres (Wärtsilä, 2012).

5.5.2 Caterpillar

Caterpillar describes its CE view as generating a value chain through a circular flow of materials, energy, and water. In this sense, the company's focus is to optimise the resources and maximise the total valuable lifecycle of their products, which will contribute to minimising ownership costs for their customers while improving sustainability and reducing the environmental effect of the products (Caterpillar, 2021). To achieve these goals, Caterpillar focuses on remanufacturing and rebuilding products at different levels and in various industries, such as construction equipment, solar turbines, power systems, and marine engines. The company remanufactures fundamental components and spare parts, and an online sales platform is also available for remanufactured parts worldwide.

Caterpillar separates remanufacturing and rebuilding concepts in their organisation and literature. While the latter corresponds to specific expert reconditioning efforts – such as Cat Certified Rebuilds, component overhauls at Cat dealers, etc. – remanufacturing is more than rebuilding (Caterpillar, 2021). Cat Reman returns engines and other components to their original performance specifications using various salvage techniques, strict guidelines, advanced manufacturing systems, and intense quality control at Cat Reman facilities. The main difference is that Cat Reman products are not simply refurbished or rebuilt. It is better than that, thanks to non-destructive processing methods applied to them after they are disassembled to their smallest parts and lose their original identity (Caterpillar, 2022, n.d.-b). Cat Reman components provide customers with the same quality, warranty, performance, and reliability as new Cat products, at a lower cost (Caterpillar, 2022).

Souza's previous study mentioned that Cat Reman products are sold exclusively at the Caterpillar parts distribution network ranging between 40% and 80% of a new product's price. Caterpillar also provides incentives such as a buy-back guarantee for unsold inventory, a core deposit fee for remanufactured parts, and a voluntary take-back of surplus used products at a price above the scrap value (Souza, 2014). The OEM strongly believes that their reman products enlarge their customer base by providing a more economical yet high-quality certified product to customers who otherwise would not be able to afford a Caterpillar product. Therefore, Caterpillar believes that there is no significant cannibalisation of their new product business by remanufactured alternatives (Souza, 2014), even though such risk is raised in the literature for OEMs (Kwak & Kim, 2017; Marques et al., 2021). Figure 5-5 below shows Cat Reman facilities around the world.

Figure 5-5: Caterpillar Reman Facilities (Caterpillar, 2013).

Cat Reman operates on an exchange business model where customers are initially charged a core deposit. Upon returning the cores (i.e., used parts or components), customers receive a deposit refund, leading to further reductions in owning and operating costs. Caterpillar utilises a specific core management system that oversees the handling of core returns from its dealers and inspection facilities on a global scale (Caterpillar, n.d.-a). From an environmental aspect, Caterpillar remanufactured more than two million components annually, which equals 68 million kilogrammes of end-of-life iron annually (Caterpillar, 2013). According to their latest sustainability report, of the 147 million pounds of material taken back in 2023, 88% of end-of-life materials were eligible for remanufacturing, resulting in 65-87% less manufacturing energy and GHG emissions, along with 80–90% less new materials by weight used (Caterpillar, 2024). By reducing waste, lowering greenhouse gas production, and minimising the need for raw materials, Caterpillar significantly improves its sustainability (Caterpillar, n.d.-b), while ensuring the circulation of non-renewable resources for multiple lifetimes.

5.5.3 Volvo Penta

Volvo is one of the OEMs that features the CE on their corporate website. Volvo Group acknowledges the importance of the circular economy and sustainability concepts aligning with its corporate values. To achieve this, Volvo Group is adopting a strategic approach to becoming fully circular: starting from the product design phase, focusing on remanufacturing and eventually reaching zero waste in landfills (Volvo Group, n.d.).

As part of the Volvo Group, Volvo Penta is also focused on sustainability, aligning with the company's commitment to the circular economy (Volvo Penta, n.d.-a). Volvo Penta Reman represents the company's remanufactured part and component options, which provide energy, raw material, and cost-saving alternatives while maintaining the quality, performance, and warranty of new products (Volvo Penta, 2021b).

Volvo Penta states that through the remanufacturing process, returned and used cores (parts, components, and engines) are given a new life as Volvo Penta Reman products. The industrial remanufacturing process minimises the environmental impact compared to new manufacturing by reusing up to 85% of the core. It also saves up to 80 % of the energy it takes to manufacture a new part. (Volvo Penta, n.d.-c).

To summarise Volvo Penta's remanufacturing process, it begins with the used component (i.e., the core), which is the raw material of the process. Once the cores are completely disassembled, they are thoroughly cleaned and inspected to determine their condition. Cores not fulfilling Volvo Penta's requirements are discarded and sent to recycling for raw materials (Volvo Penta, 2021b, n.d.-b). Components that meet the criteria are restored to new conditions. Wear parts, and those not fulfilling the requirements are replaced with new genuine parts (Volvo Penta, 2021b). Ultimately, remanufactured products and components consistently fulfil the latest technical specifications. Components such as diesel engines are carefully tested to verify product performance when they are reassembled (Volvo Penta, 2021a).

Volvo Penta underlines that their remanufactured components are technically new. The remanufactured and new marine engines are assembled in the same assembly line and undergo through the same testing processes. Therefore, the quality is equal to that of a brand-new engine. They look the same as a new one, are as durable as a new one, and have the same warranty conditions as a new one (Volvo Penta, 2024). Additionally, remanufactured marine engines result in up to 60% of materials being reused and up to 56% of CO_2 emissions being reduced compared to new engine production (Volvo Penta, n.d.-c). In other words, the used components have been given a new life as remanufactured products with minimum environmental impact.

Similar to some other OEMs in the industry, Volvo Penta includes a core fee in the invoice, which is refunded upon the return of the core to Volvo. This way, Volvo Penta incentivises customers to return their cores for CE practices, promoting sustainability in their operations. Additionally, this core fee system helps streamline the return process and ensures a more efficient supply chain for Volvo Penta (Volvo Penta, 2021b).

5.5.4 *mtu* – Rolls-Royce Power Systems

As described on its corporate website, *mtu* offers remanufacturing services through two main solutions: "*mtu* Factory Reman Solutions" and "*mtu* Factory Overhaul Solutions". These services aim to restore used components to brand new condition with consistent performance, service life, quality, and a full OEM warranty. On top of that, *mtu* offers fixed pricing and turnaround times up front to their customers (*mtu*, n.d.-a).

According to the company's internal classification, "Factory Overhaul Solutions" corresponds to overhauling a customer's equipment or component to like-new condition, which means the same performance, product life, and quality as a newly manufactured alternative. On the other hand, "Factory Reman Solutions" provides a faster solution in which a remanufactured product is offered to the customer. The Reman alternative comes with fixed pricing, less expensive than the new alternative, and fixed lead times (*mtu*, n.d.-a). Overall, *mtu* suggests that opting for Factory Reman Solutions can minimise potential downtimes by directly replacing customers' current equipment with remanufactured units available in the company's inventory (*mtu*, n.d.-b).

Like several other OEMs in the maritime industry, *mtu* is carrying out a remanufacturing process combined with a core collection strategy. As depicted in their core collection programme in Figure 5-6, customers submit a predetermined core deposit. Subsequently, *mtu* evaluates and accepts the core, issuing a credit based on the condition of the core components (*mtu*, 2019, n.d.-b).

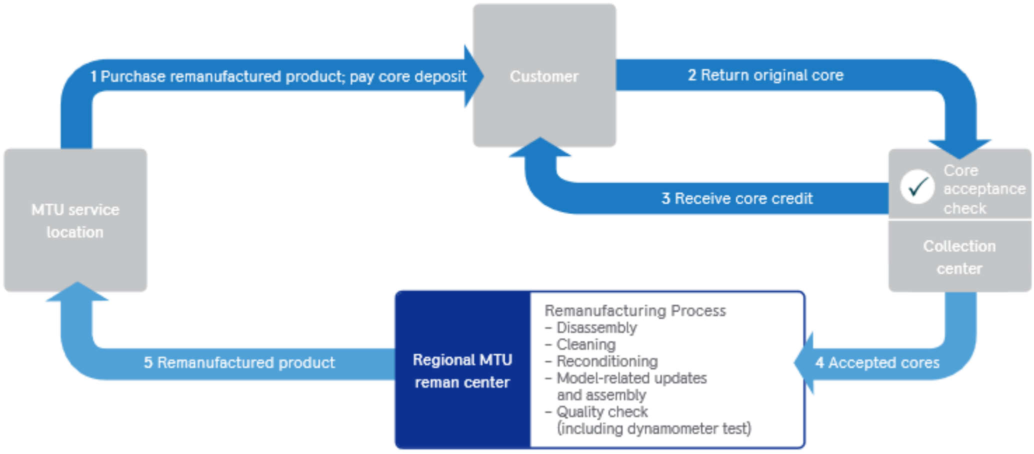


Figure 5-6: ***mtu*** core exchange programme (***mtu***, 2019).

The advantages of *mtu*'s Factory Reman and Overhaul Solutions include adherence to factory quality standards, optimal performance, reduced acquisition and operational expenses, energy and resource conservation, waste and CO2 emission reduction, and extension of the lifespan of non-renewable products (*mtu*, 2019).

The remanufacturing process at *mtu* involves sequential steps, including disassembly and cleaning, investigation, reworking, reassembly, acceptance testing, and final preparations. Figure 5-7 below presents some photos from *mtu* remanufacturing operations (*mtu*, n.d.-b).

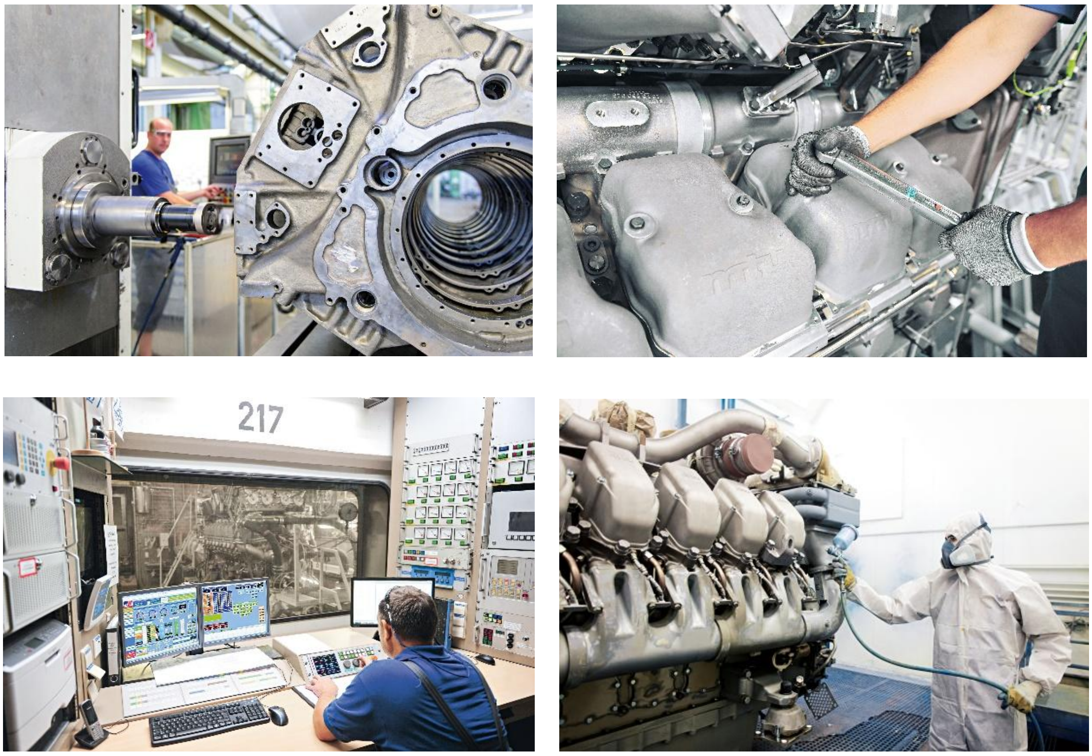


Figure 5-7: ***mtu*** remanufacturing process (***mtu***, n.d.-b).

5.5.5 Cummins

Cummins considers remanufacturing processes as one of the company’s true differentiators and key sustainability practices worldwide, and the company has been investing in advanced manufacturing technology to maximise its remanufacturing efficiency. Additionally, new Cummins engines are built with remanufacturing in mind, knowing that up to 85% of an engine can be remanufactured (Cummins, 2021). The company offers a more affordable and high-quality option (called “Cummins ReCon”) to its customers by integrating the new product and remanufacturing businesses (Cummins, n.d.-a).

Figure 5-8 below represents a simplified version of Cummins's closed-loop supply chain approach from research by Souza. In the figure, the forward flows consist of new engines and/or engine parts (water pumps, turbochargers, etc.), and the reverse flows consist of used or remanufactured products (Souza, 2013).

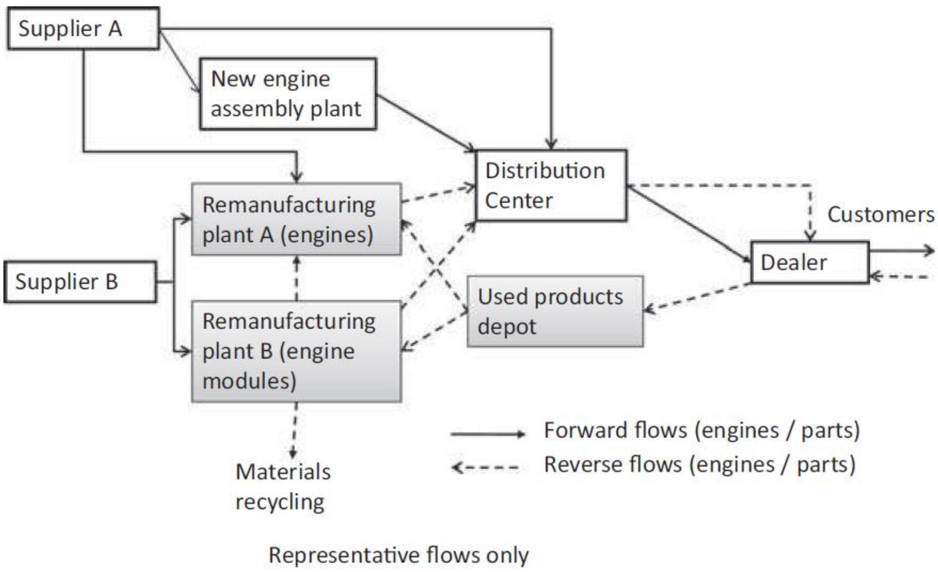


Figure 5-8: Closed-loop supply chain of Cummins (simplified), from (Souza, 2013).

Cummins ReCon marine engines match up with what other OEMs call remanufactured components. During the process, the engines are disassembled completely, thoroughly cleaned, inspected, fitted with new parts as needed, and then assembled, tested, and guaranteed like-new performance, reliability, and quality at an advantageous price (Cummins, n.d.-b).

Cummins reports that 85% less energy is required to produce a reman engine, which avoids producing 400 million pounds of greenhouse gases and reclaims 70 million pounds of material. Moreover, 67% of the company's common assembly sales—such as turbochargers, fuel systems, pumps, etc.—are reman components (Cummins, 2021).

5.5.6 Third-party Engine Reconditioners

Many non-OEM companies focus on reconditioning marine engines and other components in the industry. They provide independent repair services, usually serving multiple OEM brands and cooperating with shipowners, shipyards, and consultants.

Although third parties lack OEM-level capability and capacity, most of them can carry out reconditioning operations at various levels. Some companies may salvage reusable parts and supply replacements needed to recover the engine from used or second-hand markets. Goltens can be considered an example, as it is an independent repair services company that serves components from different brands within the maritime industry (Goltens, n.d.-b). As an engine reconditioning example, Goltens restored an end-of-use 2400 KW marine auxiliary diesel engine after a catastrophic failure. The company salvaged the crankshaft and found used engine blocks on the second-hand market. Then, after machining operations and restorative treatments, the company overhauled the engine successfully (Goltens, n.d.-a). Despite destructive applications and not being entirely remanufactured, this operation can still be classified under the circular economy concept, considering the saved product life of a severely damaged and old component. Goltens' successful restoration of the marine auxiliary diesel engine exemplifies how third-party businesses can contribute to a circular economy by salvaging and reconditioning components rather than discarding them. This process not only extends the life of products but also reduces waste and helps minimise the environmental footprint of industrial operations.

5.6 Engine Remanufacturing Process

Marine engine OEMs usually prefer a core deposit strategy to facilitate the return of used components from customers to manufacturers, enabling a reverse supply chain. In the industry, core component flow typically involves dealers, particularly for OEMs with extensive service networks. On the other hand, some OEMs carry out the core component flow through their organisations in a more centralised structure. There are dealers who have improved their capabilities and capacities by collaborating with OEMs and making technological investments. Many ship owners or operators in the sector prefer remanufacturing applications conducted by competent dealers, particularly if they want their components returned in like-new condition, rather than exchanging components.

As mentioned in Section 4.3 , due to intensive regulations in the maritime industry, marine engines go through a series of inspection and certification processes in the design and manufacturing stages. However, there are currently no specific certification processes or rules established by classification societies for the remanufacturing operation of engines. Based on the information obtained from the literature and the

OEMs examined in this research, a standard remanufacturing process is revealed for marine engines in Table 5-1 as follows (Okumus et al., 2023c):

Table 5-1: Marine engine remanufacturing phases (Okumus et al., 2023c).

Phase I
1. Disassembling the engine completely, 2. Cleaning: rust and paint removed from all parts,
Phase II
3. Inspecting, measuring, and evaluating all parts against factory tolerances and wear limits, 4. Crack testing for necessary parts, 5. Identifying modernization requirements (if any), 6. Documentation of results and findings,
Phase III
7. Reworking and machining parts and components to achieve brand-new tolerance requirements, 8. Initiating the reassembly process by incorporating both remanufactured and new parts 9. Incorporating any product updates or upgrades using the most up-to-date tools and standards
Phase IV
10. Testing the engine by replicating the rough field conditions 11. Documentation of engine performance during tests, evaluation, and assessment 12. Customer and/or classification society participation (optional)
Phase V
13. Painting 14. Concluding with preservation and packing processes

The remanufacturing process outlined in Table 5-1 serves as a standardised structure followed by many marine engine OEMs and authorised dealers to restore engines to like-new condition. The detailed phases, from disassembly and cleaning to final testing and packaging, ensure that remanufactured engines meet the necessary performance and safety standards. This summary provides a clear overview of remanufacturing processes, yet it must be demonstrated for practical marine applications in real-world settings to understand its effectiveness and economic impact.

In the following section, a case study is presented to demonstrate how this remanufacturing process is applied to a high-speed marine engine. The case study offers an in-depth look into the specific steps taken during the restoration process, as well as the tangible benefits of remanufacturing in terms of cost savings and engine performance. This practical example highlights how the theoretical remanufacturing process translates into measurable outcomes in the field.

5.7 Marine Engine Remanufacturing Case study

5.7.1 Summary of Reconditioning Operation

Continuing with the remanufacturing, this case study focuses on the rebuilding process of the main engine of a high-speed passenger ferry operating in the Aegean Sea. The engine was built in 2009 with 2300 RPM and 1450 HP. The vessel's maximum design speed is 30.9 knots, and two high-speed diesel main engines generate the propulsion power. The fleet manager of the vessel's owner company has sent the engines for rebuilding at around 9500 machine hours after their last overhauls to the authorised dealer of the engine manufacturer in the region. The dealer possesses the capacity and expertise to refurbish medium-sized marine engines. Figure 5-9 depicts the initial condition of the case study engine upon its arrival at the dealer's equipment rebuild centre.

Figure 5-9: Engine's arrival at the dealer's equipment rebuild centre.

In the preparation step, the dealer has conducted on-site controls and engine fluid analysis before removing the engine from the vessel. After remanufacturing approval was granted by the shipowner company, the remanufacturing phases given in Table 5-1 were initiated. In the first phase, the dealer disassembled the engine in their rebuild centre while constantly checking for any failure traces. After that, all parts were cleaned, and rust and paint were removed. At this stage, Figure 5-10 illustrates various examples of part cleaning procedures.

Figure 5-10: Part cleaning examples.

In phase two, all the parts (such as the cylinder block, all galleries and holes, crankshaft, all bearings, journals, camshaft, pistons, piston pins, connecting rods, oil jets, cylinder cover, valve springs, rotocoils, liners, turbochargers, valve mechanism, oil pump, water pumps, gear bearings, and so on) were inspected and evaluated. All parts undergo inspection and evaluation in adherence to the factory tolerance limits, as well as in accordance with the OEM's guidelines and remanufacturing procedures.

Apart from wear and tear, curvature and shaft deflection measurements were also carried out, as shown in Figure 5-11 and Figure 5-12 below. For different parts, the tolerance limits in measurements ranged from 0 to 0.15 mm, equating to a precision level of ‰0.36. At the same time, the dealer carried out crack testing on all necessary parts. There has been no required product upgrade for the engine since its last major overhaul. All measurements and findings, including scratches and cracks, were photographed and recorded.

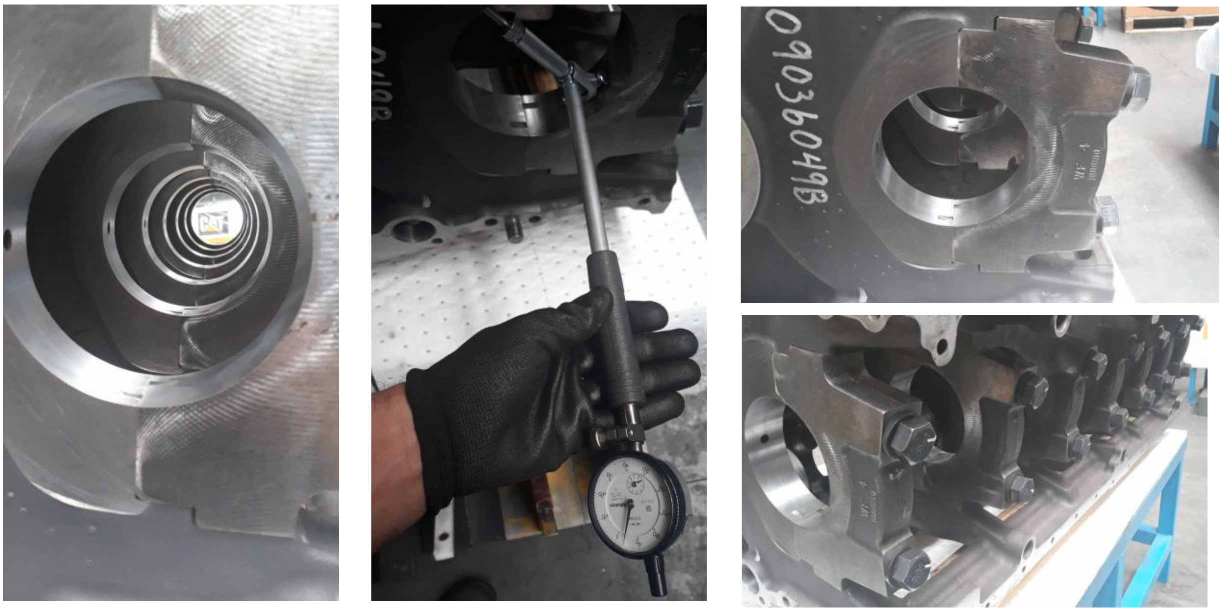


Figure 5-11: Measurement of main and crankshaft bearings and main caps.

Figure 5-12: Camshaft curvature and gears were checked, all lobs were inspected and measured.

This particular engine's cylinder liners and crankshaft journals were found defective. Therefore, in Phase III, the dealer carried out several restorative operations to reuse valuable parts such as the engine blocks and crankshaft. Other worn or faulty parts identified in Phase II, such as piston bushings, turbocharger shafts, and several valve mechanism parts, were replaced with new ones. So, the engine was reassembled using remanufactured and new parts at brand-new tolerance limits.

In Phase III, the dealer restored all salvageable core parts within their capabilities (via machining, honing, polishing, etc.) and reused them. For instance, the crankshaft has been restored and reused, as displayed in Figure 5-13. However, some other parts were restorable with only the manufacturer's technical capabilities, so they were returned to the manufacturer to be utilised once again. Finally, parts beyond recovery were sent to a metal recycling facility.

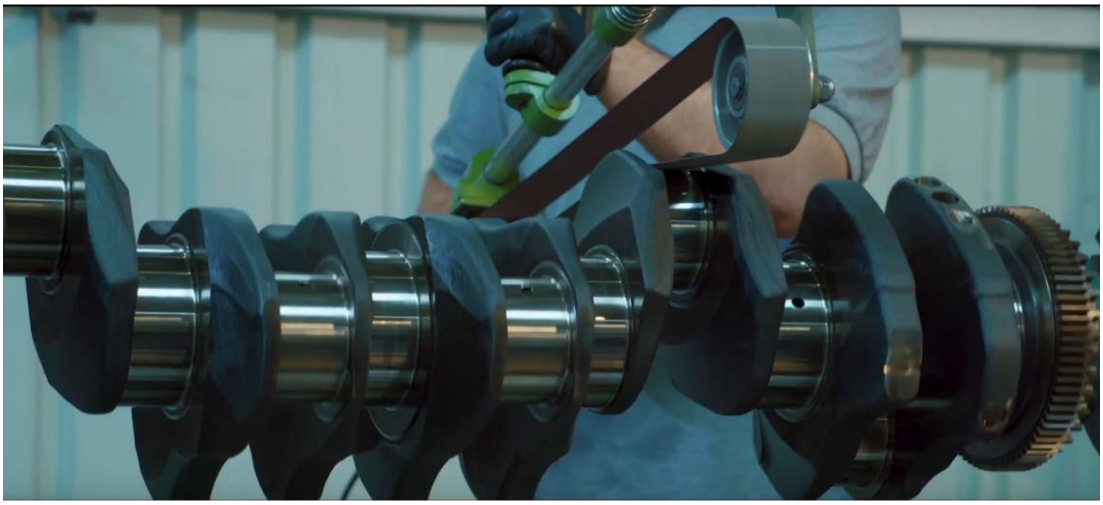


Figure 5-13: Crankshaft polishing after grinding operation.

After reassembly, in Phase IV, the engine was tested for rough operating conditions on a dynamometer at the dealer's engine testing facility. All metrics—pressures, temperatures, and engine performance—were monitored during the test, and leakage tests were carried out. Figure 5-14 below shows the dealer's engine test facility control room. With the participation of the customer's technical staff, the performance of the machine was recorded during the tests. The performance results closely matched those of a newly manufactured engine. As shown in Table 5-2, the reman engine performs on par with its newly manufactured alternative.

Figure 5-14: Engine test facility control room.

Table 5-2: The remanufactured engine's performance comparison with its new built factory test performance.

Test Element	Unit	Difference
Full Load Power	HP	-0.1%
Engine Speed	RPM	0.0%
Constant Speed Fuel Consumption @ Full Load	g/kWh	0.6%
Fuel Pressure	PSI	0.0%
Oil Pressure	PSI	-1.7%
High Idle Speed	RPM	0.0%
Low Idle Speed	RPM	0.0%
Low Idle Oil Pressure	PSI	0.0%

Phase V: Following that, the dealer proceeded with the painting process and finally packed and sent the engine to the shipyard, where it was installed on the vessel.

Following the remanufacturing process, the classification society of the vessel engaged in the engine's reinstallation, recommissioning operations, and sea trials.

Considering test results and the overall remanufacturing process, the manufacturer allowed a five-year, 8,000-hour extended warranty for the engine. Although extended warranty packages can be purchased, today, even a newly manufactured engine comes with a standard warranty of two years / unlimited hours. A brand new alternative to this particular engine also comes with a standard warranty of two years and unlimited hours. Therefore, it is evident that both the manufacturer and dealer together stand behind remanufactured components and products, and so they go beyond standard warranty coverages. Figure 5-15 shows the before and after of the dealer rebuild process.

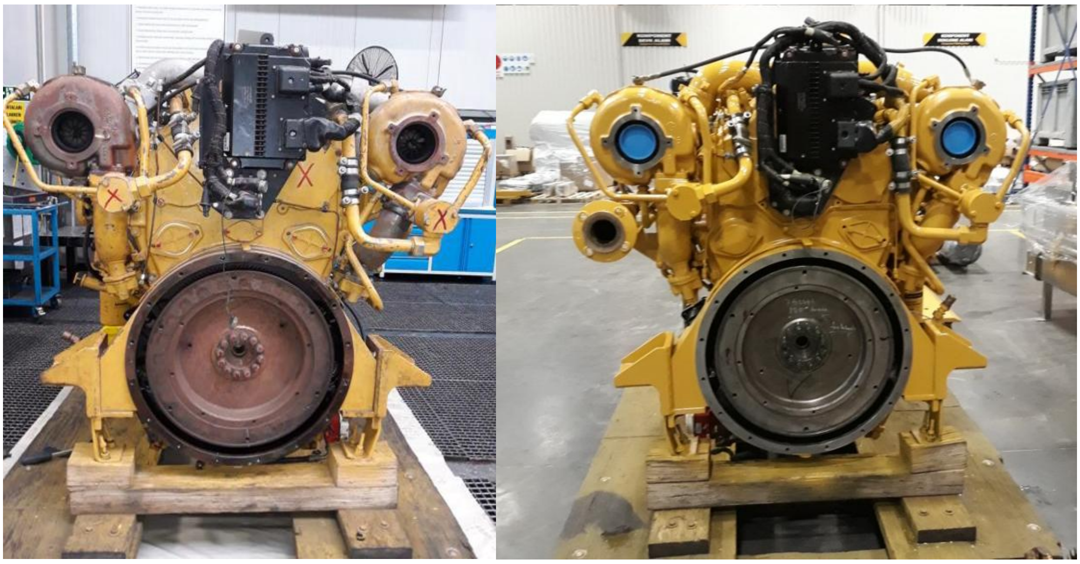


Figure 5-15: Condition of the engine, before and after the dealer remanufacturing procedure.

5.7.2 Benefits of the Case Study

This case study forms an excellent example of end-of-life marine engine and component remanufacturing solutions. Thanks to the combined efforts of local dealerships and global OEMs, the customer could be provided with tailor-made reconditioning service and minimum transportation of parts and components.

From the CLSC perspective, the case demonstrates a smart and strategic approach that includes product acquisition, reverse logistics, and flexible remanufacturing capabilities. Firstly, the customer’s high awareness of remanufacturing played a significant role in this case, thanks to the dealer's intensive efforts and strong OEM support. Therefore, increasing customer awareness for smoother product acquisition at the EoL is fundamental. Moreover, due to the collaboration between the OEM and the dealer, the remanufacturing process took place at the dealer's facility, leading to a substantial reduction in transportation costs and core part lead time. Additionally, the dealer's capacity and capabilities in remanufacturing operations are valuable and have played a crucial role in the case study.

As an alternative scenario to this case study, a trade-in/take-back strategy could have been followed. In that scenario, the customer could have purchased a remanufactured component (exchange component) directly without waiting for their engine. Subsequently, the dealer would have returned all cores to the manufacturer. The customer would have benefited from the economic advantage of remanufacturing all the same. However, in the case study presented, the customer opted for their old engine to be remanufactured.

From a technological perspective, the remanufactured engine is now equipped with various sensors and data collection devices that enable condition monitoring services. Keeping track of the engine's operating statistics and fault codes can help with future recovery or end-of-life decisions, and when combined with AI applications, it could lead to SRDM solutions. At present, a dedicated engineering team at the dealer company focuses on condition monitoring and strives to optimise equipment utilisation, encompassing the planning of preventive maintenance, repairs, and EoL solutions. The dealer, in this case, has established an extraordinary component rebuild centre; however, it is far from a mass-production plant. By their nature, rebuild operations are managed more like a job shop production system due to the diverse range of products and low volume per product model. Furthermore, while the dealer can refurbish most valuable engine parts; especially for smaller components (such as fuel injectors), returning them to the manufacturer is more advantageous. This is primarily due to economies of scale and enhanced technical capabilities present in the manufacturer's remanufacturing facilities.

Main advantages of this case study are as follows:

- Heavy parts that can be remanufactured by the dealer, such as crankshafts and engine blocks, are remanufactured locally. So, there is a considerable saving in terms of logistic costs.
- The engine was transported to the local dealer's component rebuild centre instead of being shipped to other countries or an overseas facility.

- The local remanufacturing option attracted the customer who sent its technical staff to visit multiple times during the rebuilding process.
- Parts that were remanufacturable but replaced due to the customer's request were returned to the OEM's remanufacturing facility.
- Parts found to be remanufacturable but needed beyond the dealer's capabilities were sent back to the OEM's remanufacturing facility.
- Ideally, the OEM's remanufactured part series can provide the replacement parts during a dealer's remanufacturing or rebuilding process. A combination of parts reconditioned by the dealer and parts remanufactured by the OEM would have rebuilt the engine or component. That means the engine would be 100% remanufactured. It is clear that by using remanufactured spare parts, the dealer can rebuild the engine sustainably and as circularly as possible.
- Nevertheless, because of import restrictions on some remanufactured parts in the dealer's country, they had to opt for new components instead of OEM remanufactured series.
- The OEM updated the engine's serial number, and the unit was granted a 5-year warranty.

5.7.3 Cost-benefit Analysis

After successfully completing the remanufacturing operation and commissioning the engine, this thesis conducted a cost-benefit analysis to demonstrate the financial outcome of the case study. The questionnaire results in Section 4.2 indicated around 40% cost savings for remanufactured equipment, while Souza (2013) mentioned 35% lower costs on average.

In this study, the cost-benefit analysis excludes maintenance costs because both alternatives (remanufactured and new) have the same maintenance frequency and costs. Moreover, since both alternatives have the same performance, as shown in Table 5-2, they generate the same outcome. Therefore, this section primarily evaluates the present value of costs. In the present worth comparison, disassembly/assembly labour, parts recovery costs, spare parts costs, consumable costs, and fuel consumption differences have been taken into account. Moreover, the new engine and end-of-life scrap values were also considered.

Even though it might simply originate from the sensitivity of the measuring equipment, the cost-benefit analysis was carried out with the worst-case scenario in mind for accuracy. Therefore, the 0.6% difference in fuel consumption given in Table 5-2 reflected a negative impact on the remanufactured engine as it increased fuel consumption for 10 years. Considering the ferry's operation profile, the engine will undergo a major overhaul in 7 years. However, for this analysis, it was assumed that it would take ten years to be safe, just in case. Post major overhaul, both alternatives—remanufactured and new—are expected to have the same fuel consumption.

The scrap value estimation is based on current market prices at end-of-life, which takes salvaging it for spare parts into account. The annual interest rate of 1.25% is used according to the European Central Bank's fixed rate (ECB, 2022). In Table 5-3, costs have been adjusted through normalisation to adhere to a confidentiality agreement with the dealer, which facilitated this case study for this PhD research.

Table 5-3: Normalised cost of remanufactured engine compared with the new engine.

Remanufactured Engine		**New Engine**	
Total present cost (P)	44.2	Total present cost (PWC_{new})	100
Annual cost for 10 years (A)	0.8		

For the reman scenario, the total net present value is calculated as follows:

$$PWC_{reman} = P + A * (P/A\,, 1.25\%, 10) \qquad (5.1)$$

From Equation 5.1, the remanufactured engine (PWC_{reman}) costs slightly more than half of the new engine cost, by 51.7%. If the fuel consumption difference is neglected, considering a 0.6% difference can be caused by measuring equipment's precision, the cost ratio decreases to 44.2%.

5.8 Chapter Summary

This chapter explored various strategies, technologies, and hardware solutions to improve circularity in the maritime industry. The investigation highlighted the remanufacturing practices of major marine engine OEMs, showcasing how their involvement in other industries has influenced their approaches. A comprehensive remanufacturing process for marine engines was presented, resulting in a detailed case study. The case study demonstrated that remanufactured engines perform on par with new ones in terms of performance. Moreover, the cost-benefit analysis revealed a substantial financial saving of 48.3%, with the potential to reach 55.8% compared to purchasing a new engine. These findings underscore the economic and operational feasibility of remanufacturing as an advanced circular practice, providing actionable insights for the industry. They illustrate how remanufacturing can serve as a catalyst for reducing costs, conserving resources, and extending the lifecycle of critical marine assets, supporting the maritime industry's transition toward circularity and long-term sustainability.

6 Design of a Digital Asset Tracking System as a Bridging Solution

6.1 Chapter Overview

This chapter continues the exploration of the maritime circularity framework in Phase II by focusing on digitalisation and CE relationship. It explores the material passport concept and establishes a customised database solution as its digital infrastructure. Following validation by expert opinions, the database presents a case study from a shipowner's perspective, exhibiting its practical benefits. This chapter has been partly published in the Sustainability journal (2024) issue 16(1) as follows:

Okumus, D.; Gunbeyaz, S.A.; Kurt, R.E.; Turan, O. An Approach to Advance Circular Practices in the Maritime Industry through a Database as a Bridging Solution. *Sustainability* **2024**, *16*, 453. https://doi.org/10.3390/su16010453

6.2 Background

As the maritime industry sits at the intersection of environmental sustainability and economic viability, innovative solutions are increasingly being sought to tackle these complex challenges. Overcoming these challenges and barriers to implement CE principles to maritime requires collaborative efforts between industry players, policymakers, and researchers to develop innovative solutions and promote knowledge sharing on CE practices. Circular supply chains need to recover resources at the end of a product's life to remanufacture or recycle them. These activities require collaboration, yet despite the long-standing recognition of the challenges in managing collaborative networks (Bititci et al., 2007), current efforts are limited on coordinating such networks in a CE context (Marques-McEwan & Bititci, 2023).

This study revealed a severe lack of digital infrastructure for data availability in Chapter 4, which hinders the dissemination and use of vital information needed for circular practices. Addressing this issue would involve developing digital platforms and systems that can facilitate data collection, analysis, and sharing across the maritime sector. Additionally, promoting awareness and training on the benefits and implementation of circular economy practices can help stakeholders overcome resistance to change and foster a culture of sustainability in the industry.

Indeed, the current environment highlights a significant gap in the transition towards a circular economy in the maritime sector. Currently, there needs to be a working, industry-wide infrastructure to facilitate the transition from a linear to a circular economy in the maritime sector, and even theoretical explorations of this topic are limited. This novel research aims to bridge this gap by proposing a robust database solution that is the first of its kind, designed to support the industry's transition towards circularity. This database will substantially benefit all industry stakeholders by providing a much-needed digital backbone for implementing CE principles. The structure of this database and its numerous benefits will be presented in detail in this chapter.

6.3 Chapter Methodology

This chapter consists of a ten-step methodology, corresponding to four main research phases: stakeholder consultation and needs analysis (Steps 1-3), investigation of best practices (Step 4), database development (Steps 5-8), and testing, validation, and impact estimation (Steps 9–10). Figure 6-1 illustrates the methodology adopted for this chapter. The first research phase (Steps 1-3) originated from the stakeholder engagement events in the Phase I of this thesis .

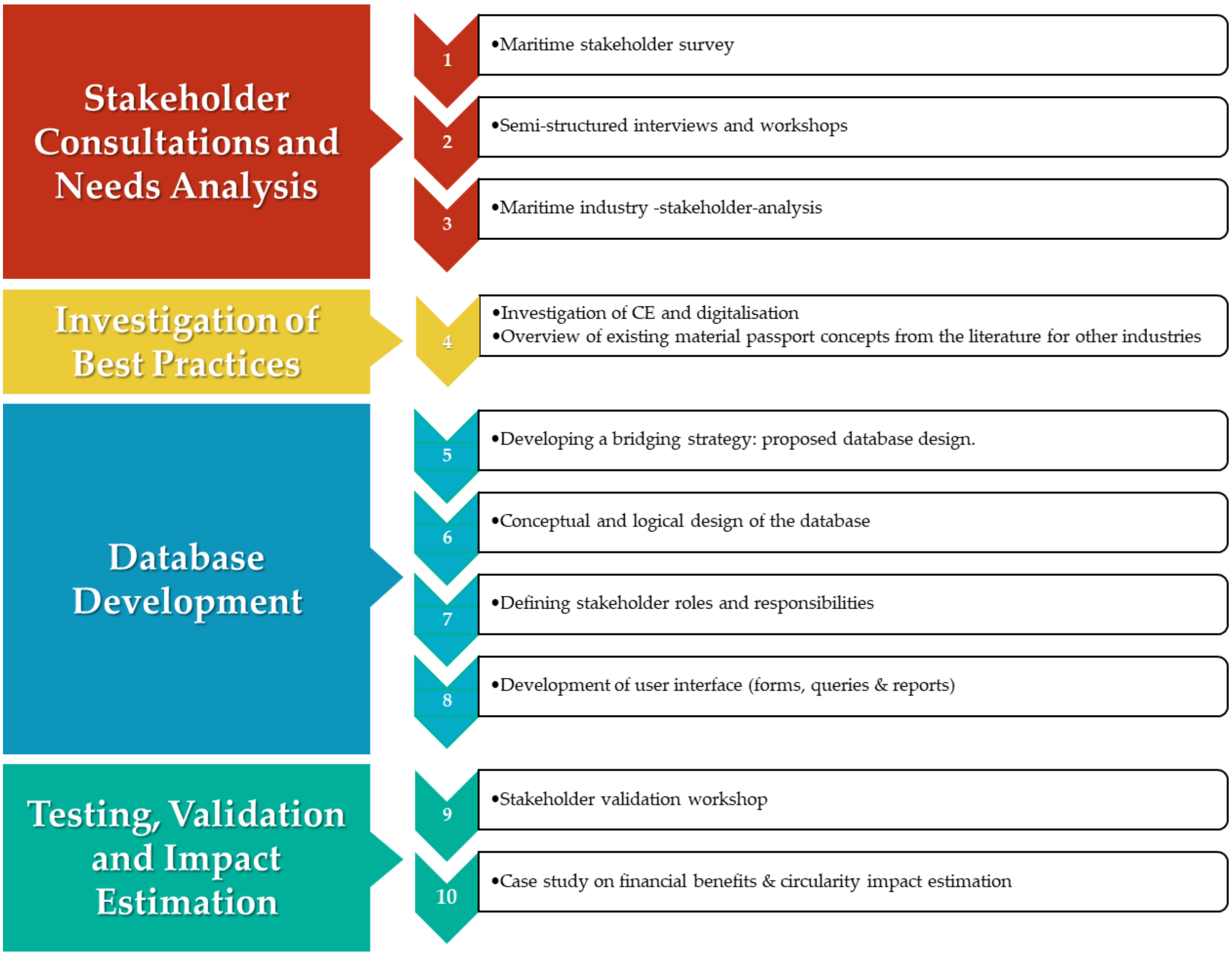


Figure 6-1: Chapter methodology.

As the first step in this chapter's methodology, a maritime stakeholder-focused questionnaire, which was previously presented in Section 4.2, was designed and reached out to 83 individuals from different stakeholder groups. Then, between 2021 and 2023, two online and three in-person semi-structured interviews and workshops were conducted with maritime professionals regarding enabling CE practices for the maritime industry. Step 3 combines the survey results and interview workshop outcomes to form a maritime industry analysis. Subsequently, the connection between the circular economy and digitalisation was investigated in Step 4, which included diving into the details of material passports and eventually developing the maritime asset tracker (MAT) concept. Following these, the chapter methodology involves developing a database solution (Steps 5-8) as a bridging strategy for enhancing the circularity of marine assets. This process includes creating a comprehensive database that can track and manage the lifecycle of marine assets, including information on their catalogue specs, usage, upkeep, and disposal. The database solution aims to provide a centralised platform for stakeholders in the maritime industry to access and contribute data, facilitating better decision-making and resource optimisation for circular economy practices. In Step 9, a stakeholder validation workshop was organised to collect feedback and ensure end-user adoption of the suggested framework. Additionally, a case study on a sample ship was conducted in Step 10 to demonstrate the financial benefits and circularity impact.

6.4 Stakeholder Needs Analysis

The anticipated increase in world trade volume further highlights the importance of sustainable practices within the maritime sector. Unfortunately, the shipping industry's current environmental footprint is significant; around 10–15% of sulphur oxide (SOx) and nitrogen oxide (NOx) emissions globally are attributed to the maritime industry (Bjerkan & Seter, 2019) .

Merely focussing on the age demographics of the current fleet, the average age of cargo vessels stands around 22 years, as shown in Figure 3-1 (Okumus et al., 2023a; UNCTAD, 2022a). This fact implies that a considerable portion of the fleet may not be equipped with the latest smart technologies, such as IoT sensors, real-time condition monitoring, or other I4.0 advancements. However, this also highlights an opportunity for the sector to leverage a fundamental digital infrastructure to enable circular economy principles to extend marine assets' lives and extract more value at their end-of-life phases.

Notably, the rise of digitalisation offers potential avenues to integrate advanced circular economy principles within the maritime domain. Nevertheless, there still needs to be a cohesive, industry-wide digital infrastructure to facilitate the adoption of a circular economy within the maritime sector. As of now, both empirical implementations and theoretical studies in this sphere are extremely limited, apart from a couple of literature review studies to identify the gaps (Jensen & Remmen, 2017; Milios et al., 2019; Okumus et al., 2023b; Okumus et al., 2023c; Wahab et al., 2018) and the application of 3D printing on-board for spare parts (Silva et al., 2023). Moreover, the path to a circularity framework within the maritime industry is not straightforward. It is complex and requires gathering comprehensive feedback from all its stakeholders, namely ship designers, OEMs, shipyards, ship owners or operators, classification societies, regulatory bodies, port authorities, and local or international NGOs.

Most of the large, well-known OEMs in the maritime sector also provide products to other industries such as oil and gas, power generation, construction, etc. Their circularity levels in those sectors are generally much higher than in the maritime sector (Okumus et al., 2023c). In other words, even though they have the capability to reuse or remanufacture, for instance, they are very limited in carrying out those restorative circular operations in the maritime industry, and this is mainly because of a need for a proper reverse supply chain (Okumus et al., 2023a; Okumus et al., 2023b; Okumus et al., 2023c). A closed-loop supply chain in the maritime industry is necessary for OEMs to fully implement circular practices. Without an efficient system for collecting and refurbishing used products, the potential for reusing or remanufacturing in the sector remains largely unexplored. Consequently, OEMs in other industries have been more successful in achieving higher circularity levels than their counterparts in the maritime sector.

Feedback and insights from maritime stakeholders are invaluable to forming a healthy closed-loop supply chain in the maritime domain. Only through this collaborative effort can a digital roadmap be developed that suits the sector's unique needs. Furthermore, this collective strategy should focus on more than just newly built vessels. It should also encompass the existing fleet, providing a bridging solution that ensures both older and newer ships can operate sustainably while maximising value extraction. The maritime industry's transition towards decarbonisation, green shipping, and the adoption of the circular economy is essential for environmental resilience and a significant step towards a sustainable and prosperous future for world trade. In that sense, this section will enclose some key results from the maritime stakeholder survey, interviews, and workshops conducted within this PhD research.

6.4.1 Stakeholder Survey Takeaways

The maritime stakeholder survey introduced in Section 4.2 provided diverse representation from different stakeholder categories within the maritime industry: 83 participants from various maritime stakeholder groups with an average experience of 10.5 years. Moreover, a significant portion of the participants are in decision-making positions in their organisations. This indicates that the survey has captured a wide range of perspectives and insights from key individuals who significantly influence the maritime industry. Including decision-makers in the survey ensures that the findings and recommendations derived from this study will strongly impact future policies and strategies within the sector. According to the results, even though many barriers prevent a smooth and quick transition to a circular maritime industry (Okumus et al., 2023b), the potential is evident. OEMs participating in the survey are especially aware of this potential. They expressed their willingness to invest in research and development to explore circular economy practices further. Additionally, the survey revealed that stakeholders believe collaboration between different maritime industry actors is crucial for successfully implementing circularity initiatives.

The survey contains specifically designed questions for different stakeholder groups. Depending on their role in the maritime sector, the participants were asked for different perspectives on the barriers and potential of transitioning to a circular maritime industry. This approach allowed for a comprehensive understanding of the challenges faced by various stakeholders, including shipbuilders, port authorities, and shipping companies. The diverse responses provided valuable insights into the specific areas that need to be addressed to facilitate a successful transition towards a more sustainable and circular maritime industry.

As illustrated in Figure 4-11, 86% of OEMs have declared that they are able to carry out advanced circular practices such as reuse, remanufacture, and repurpose operations for on-board engines and hydraulic equipment. Half of the shipyard stakeholders have joined them in this declaration. Nearly two-thirds of this group stated that they have sufficient technical capabilities to remanufacture the components onboard vessels. The results demonstrate a strong presence of remanufacturing know-how in the industry, particularly among OEMs.

After learning about the industry's capacity to utilise these circular principles, participants from academia and OEMs are more precisely asked about their thoughts and intentions regarding RRR operations. There is a strong interest among academics and manufacturers in the industry, as shown in Figure 4-12, where more than 80% of the participants approve of these circular activities and prefer to carry them out. This high level of approval and willingness indicates a growing recognition of the economic and environmental benefits of RRR operations. It also suggests a strong potential for collaboration between academia and OEMs to develop and implement these circular practices in the maritime industry more extensively. On top of that, to further discover the intentions of OEMs and shipyards, this group was asked whether they would consider participating in a remanufacturing hub concept in the future. On a 1–5 Likert scale (1 meaning no and 5 meaning definitely yes), the stakeholder group responded with 3.74 points, as illustrated in Figure 4-13, responding "probably yes" to the question. Moreover, in the follow-up section, none of the participants directly rejected the idea of collaboration with third-party remanufacturers, as depicted in Figure 4-14.

Overall, the questionnaire showed substantial interest among OEMs and shipyards in remanufacturing valuable marine components and equipment. A moderate percentage supports the remanufacturing hub concept, too. While OEMs and shipyards did not express a definitive "yes" response, their average score of 3.74 suggests they are open to the idea. Additionally, the fact that none of the participants outright rejected collaboration with third-party remanufacturers indicates a potential willingness to explore partnerships in this area. Also, remanufacturing capability already exists within some OEMs and shipyards, which increases the chances of accurately applying circular economy principles in the maritime sector.

6.4.2 Insights from Interviews and Workshops

Two online (51 and 12 participants, respectively) and three in-person (14, 8, and 9 participants, respectively), semi-structured interviews and workshops were conducted with various maritime stakeholders regarding enabling circular economy practices in the sector (Okumus et al., 2024b). In these events, a wide range of topics have been discussed, from the potential benefits of circular economy practices to existing barriers in the maritime domain. Best practices from other transportation industries, such as automotive and aviation, along with power generation, and construction industries, have also been considered. The primary objectives were strategies to address the current gaps and pave the way for a successful circular transformation.

Maritime professionals are aware that a viable solution enabling circular economy principles in the maritime domain should be applied to existing fleets, considering the presence of over 56,000 vessels of 1,000 gross tonnes (GT) and above sailing globally (UNCTAD, 2023) . In this sense, three main strategy groups are identified: The first step is focused on creating a circular mindset for entire stakeholder groups, followed by the essential steps to realising maritime circularity, and the final strategy set is more concerned with the most advanced future solutions after the successful transition.

Creating a circular mindset includes building industrywide awareness, from ship designers to end customers (cargo owners), and everyone in between should be acknowledged, trained, or educated on the benefits and principles of maritime circularity. This strategy also fosters collaboration and knowledge-sharing among stakeholders to drive innovation and problem-solving in the industry. Additionally, it emphasises the importance of integrating circularity into policies, regulations, and industry standards to create a conducive environment for circular practices. Therefore, international authorities and classification societies have an important role in motivating other stakeholders, especially ship design and building communities. Such regulations and standards are necessary to ensure the widespread adoption of circular practices in the maritime industry. Without clear guidelines, shipbuilders may hesitate to invest in circular design and construction methods, fearing potential conflicts with existing regulations. Furthermore, the lack of standards makes it difficult for shipowners and operators to assess the environmental performance of different vessels, hindering their ability to make informed decisions regarding sustainable shipping options.

Essential strategies to realise maritime circularity consist of a holistic approach to the lifecycle impact of vessels, digital asset tracking systems, and certified equipment remanufacturing. A holistic approach means taking into account shipbuilding emissions, raw material and recycled material contents and energies, as well as operation emissions due to fuel consumption and other consumables. In recent years, the goal of reducing emissions from shipping has become increasingly popular; however, most of the research has ignored the emissions during the shipbuilding, repair, and recycling stages, as their ratio is minimal compared to the operation stage. However, we have limited natural resources to produce as many goods as needed. Hence, it is crucial to consider raw material consumption when producing any marine equipment or a complete vessel. Lifecycle analysis (LCA) methods might be extremely handy at this point, and in the near future, most of the newly built vessels might benefit from standardised LCA applications. Asset tracking is an absolute must to enable almost all of the principles of the CE and even accurate LCA practices for new vessels. Following a component through its lifespan and accounting for all materials or subcomponents that might be reused, remanufactured, or recycled is a crucial step in this strategy. Even a basic asset tracking system that depends on its users to be operated manually might bring significant benefits to the industry, such as enabling remanufacturing through facilitating core component collection or estimating the end-of-life value of vessels or onboard equipment more accurately. From the circular economy aspect, the certified equipment manufacturing process is a complementary part of the essential strategy group. Certification here means having OEM and classification society approvals for the remanufactured products to be used in new or existing vessels without any issues. This certification ensures that the remanufactured products meet the required quality and safety standards, reassuring shipowners and operators. Additionally, by promoting remanufactured products, the industry can reduce its reliance on new raw materials and contribute to a more sustainable and resource-efficient future.

The final strategy involves long-term, advanced solutions following a successful circular economy transition. These strategies include real-time condition monitoring for marine assets using the Internet of Things (IoT) and Smart Recovery Decision-Making Systems (SRDM) to determine the optimum time and method of end-of-life practices and remanufacturing hubs to utilise economies of scale from reusing or remanufacturing operations. These strategies aim to maximise the lifespan of marine assets and minimise waste generation. By implementing IoT technology, real-time data can be collected to monitor the condition of assets, allowing for proactive maintenance and timely decision-making on when to retire or repurpose them. Additionally, establishing remanufacturing hubs will reduce the need for new production and create opportunities for job growth and economic development in the circular economy sector. Therefore, the next section will discuss the circular economy and digital solutions.

6.5 Circular Economy and Digital Solutions

6.5.1 CE and Digitalisation

The CE refers to a method of economic growth that emphasises reusing and recycling resources rather than creating new ones. In other words, it is a regenerative alternative to the take-make-waste extractive economic paradigm because it seeks to preserve as much value as possible in products, parts, and materials. In this sense, the CE paradigm is a visionary framework that aims to change industries into regenerative systems by putting more emphasis on closing, narrowing, and slowing down energy and material loops (Boukhatmi et al., 2023; Geissdoerfer et al., 2017). The momentum of this concept has increased alongside rapid technological advancements, with digitalisation playing a crucial role in enabling the circular economy. Digitalisation refers to integrating digital technologies and data-driven processes into various aspects of industries and systems. Digitalisation is being incorporated across various sectors to ensure sustainable material and energy utilisation without compromising the prospects of future generations (Mulhall et al., 2022). Innovative digital techniques have been applied across several industries and nations to integrate crucial CE technologies. These instruments include metrics for circularity, life cycle costing, life cycle impact assessment, and material passports. Adopting such instruments, fuelled by digital innovation, has paid off in both environmental and economic terms (Hoosain et al., 2020). In other words, the interaction of CE principles with digitalisation capabilities sets the stage for a healthy combination of economic development and environmental conservation.

A notable research gap exists concerning digital tools to boost CE adoption in the maritime sector. A predominant issue is the deficient data sharing, making it exceptionally difficult to measure the success of the circular economy principles and to come up with accurate circularity indicators (Serna-Guerrero et al., 2022) . To tackle this, the EU's Circular Economy Action Plan has proposed novel models driven by digital tools such as the Digital Product Passport (DPP), which provides essential product details (Boukhatmi et al., 2023; Walden et al., 2021). These innovative tools can play an instrumental role in expanding circularity in the maritime sector, provided their potential is realised and harnessed effectively. The details of the DPP and Material Passport (MP) concepts will be discussed in the next section.

The CE landscape is complex and requires several data types to ensure effective implementation. Luoma et al. (2021) defined four key data types that are important for the effective implementation of the circular economy. These data types include customer behaviour data, which helps understand consumer preferences and behaviours; product or service lifetime data, which tracks the lifespan and usage patterns of products or services; system performance data, which measures the efficiency and effectiveness of the CE system; and material flows data, which tracks the movement of materials throughout the CE. Each data type uniquely supports the CE based on factors such as industry dynamics, product or service characteristics, and environmental conditions. As sectors and businesses increasingly move towards a circular economy, traditional business practices will face significant challenges. Enhancing CE would change prior linear supply chains into more open examples of cross-sectoral collaboration (Köhler et al., 2022), forcing organisations to align their interests in order to support sustainable growth (Herrero-Luna et al., 2022). As a result, organisations are more reliant on active cooperation across many actors to realise, provide, and participate in value creation (Chesbrough et al., 2018; Serna-Guerrero et al., 2022). This necessitates the transformation of raw data into actionable insights (Chen et al., 2015), possibly through external collaborations (Gao et al., 2020; Kristoffersen et al., 2021), thereby amplifying the significance of trust within the value chain (Rajala et al., 2018; Serna-Guerrero et al., 2022). Ultimately, data acts as a catalyst, supporting various CE principles (6R) and leveraging larger and closer-looped supply chains to enhance the circularity of the overall industry.

Even though the significance of data in the CE concept is widely recognised, there has been a lack of comprehensive investigation into its application for enhancing circularity on a systemic scale (Serna-Guerrero et al., 2022). Various data types hold distinct value propositions within the CE ecosystem (Gupta et al., 2019). However, the majority of the cases presented in the literature have so far focused on a single strategy rather than embracing a comprehensive system-centric perspective or holistic consideration (Acerbi & Taisch, 2020; Serna-Guerrero et al., 2022). Such an approach results in an incomplete representation of both processes related to CE and the roles and responsibilities of the corresponding stakeholder groups. Thus, a broader perspective with a comprehensive industry viewpoint is needed for further advancements in the circular economy. Sharing information digitally is essential to accelerating the CE transition (Jäger-Roschko & Petersen, 2022). In recent years, digital platforms have been recognised as enablers of the CE because they facilitate transactions between networks that aim to reduce resource usage and waste generation (Boukhatmi et al., 2023; Ciulli et al., 2020; Konietzko et al., 2019). The future of CE lies in harnessing these digital tools and platforms, translating data into actionable measures that promote circularity on a grand scale.

6.5.2 Existing Material Passport Concepts: MP, DPP, and CMP

Many heavy industries, including transportation, power generation, and construction sectors, take up the challenge and aim to achieve environmental sustainability along with economic viability. On the other hand, advanced circular economy principles such as reuse, remanufacture, and repurpose become possible only if material movements are tracked, and possible pathways are defined. One of the innovative solutions to address these issues is Material Passports (MP), which can be utilised case-by-case to assist decision-makers regarding the most favourable circular end-of-life practices amongst the 6R. For instance, in the construction industry, Schaubroeck et al. (2022) have emphasised the importance of material pathways, the cascade database, and its potential in in-use buildings.

The term "material passport" has been used in the literature under various names, such as "material passport" (MP), "digital product passport" (DPP) (Çetin et al., 2021;

Honic et al., 2021), and "circular material passport" (CMP) (Göswein et al., 2022), among others. Nevertheless, the essence of these concepts lies in their similar purposes and functionalities. These different names for the concept of a material passport reflect the various contexts and perspectives discussed in the literature. Despite the variations in terminology, all these terms refer to a tool or database that provides information about the materials used in a product or building, enabling better management of resources and promoting circular economy principles. Indeed, MPs are defined as data sets that describe the features of a product in order to analyse the product's current use as well as its potential for end-of-life opportunities such as reuse and recycling (Schaubroeck et al., 2022). The features may include the material composition of the product, such as valuable metals or rare earth elements, as well as the products' subcomponents and parts, as they can be utilised separately from the prime product at the end-of-life stage.

Similarly, as the name suggests, the DPP concept specifies a digital passport that can be used to track tangible items. The goal is to digitalise product lifecycles so that the circular economy can be adopted and expanded (Walden et al., 2021). The CMP concept broadly aligns with the MP and DPP concepts, with just one key distinction: CMP is a potential tool that seeks to support stakeholders' decision-making towards circularity during the stages of product design, use or operation, and end-of-life (Göswein et al., 2022).

Regardless of their industries, all variants of material passport systems or frameworks crucially depend on an intelligent database design. It is critical to rely on standardised, trustworthy, and consistent data on end products, equipment, subcomponent composition, and associated stakeholders, which is why digitalisation is necessary (Göswein et al., 2022). Acquiring data is critical for keeping a passport up-to-date and providing precise decision support when determining which CE principles to follow at the end-of-life stage for each product or subcomponent. In particular, data on products and assets already in use is critical because it allows for early assessments of an appropriate CE strategy at the end of the first life cycle (Boukhatmi et al., 2023). Ideally, the data acquisition can be achieved through integrated cyber-physical systems (Wilde et al., 2022) or, in other words, an I4.0 application, such as smart products utilising the IoT (Okumus et al., 2023c) . These technologies enable real-time monitoring and tracking of product usage, performance, and condition. This data can inform decision-making regarding product reuse, remanufacturing, or recycling options for each product or subcomponent, ultimately contributing to a more sustainable circular economy.

6.5.3 Maritime Asset Tracker (MAT) Concept

Following different material passport applications in the literature, this study presents the novel MAT concept, which adapts MP, DPP, and CMP concepts for the maritime industry. A fundamental issue in maritime transportation is a lack of reliable and accurate data about the current fleet, i.e., cargo vessels and valuable onboard equipment. A certain level of transparency and information sharing is needed to reach circularity. Without the digitalisation of product and process information and covering the whole product lifecycle, exploiting the circular economy implementations would be extremely impractical (Eppinger et al., 2021; Walden et al., 2021). In other words, the CE concept would remain a theory without large-scale, real-life execution. Therefore, the MAT idea aims to bridge this gap by integrating digital technologies and data-sharing platforms in the maritime industry. This would enable stakeholders to track and trace onboard equipment and products throughout their lifecycle, ensuring transparency, accountability, and efficiency in data sharing. Additionally, the MAT concept also emphasises the importance of collaboration among stakeholders in the maritime sector, such as ship owners, shipyards, OEMs, and ship recyclers, to collectively achieve circularity goals. By implementing the MAT concept, the maritime industry can move closer to realising the full potential of circular economy principles and contribute to a more sustainable industry.

Like any digital passport solution, MAT system requires a robust and efficient database structure. Within this study, a tailor-made database structure was created for this purpose through comprehensive stakeholder analysis and integrating user requirements into the database structure. The next chapter will dive into the details of the suggested database, the roles and responsibilities of maritime stakeholders, and the potential benefits of a successful implementation of MAT system.

6.6 Bridging the Gap: Proposed Database Structure for MAT

The drive towards a circular economy within the maritime industry necessitates a systematic approach to managing material information across the lifecycle of maritime assets. One significant obstacle to achieving circularity is the disjointed or siloed nature of information regarding materials, their characteristics, and their end-of-life opportunities. Bridging this gap requires a structured, secure, and easily accessible database system tailored for MAT system. From a holistic point of view, as a solution that will rapidly move the industry forward, this study suggests a database solution that covers all maritime industry stakeholders to track up-to-date equipment and component information on marine vessels. This proposed database structure will provide a centralised platform for stakeholders to access and update equipment information and ensure standardised data integrity and ease of use.

This section explores the architecture and functionalities of the proposed database system that seeks to centralise and standardise valuable onboard equipment such as main and auxiliary engines and hydraulic pumps. These pieces of equipment were selected in reference to Section 4.4.1, which shows a high RRR potential (Okumus et al., 2023c). With an emphasis on conceptual and logical design, stakeholder involvement, and tangible benefits, this PhD research present a comprehensive roadmap for implementing a MAT system database that can serve as a critical enabler for maritime circularity. This section also carries out a further database validation study using expert opinions from maritime stakeholders. Additionally, a case study was employed to showcase the financial benefits of implementing advanced circular economy practices in conjunction with the proposed digital infrastructure.

6.6.1 Conceptual and logical database design

The maritime industry does not have an infrastructure to facilitate industry-wide sharing and standardisation of valuable onboard equipment. This lack of centralised information leads to inefficiencies and increased costs for maritime stakeholders. By implementing a MAT database, we can address this issue by creating a platform that allows for a standardised database structure's conceptual and logical design. This will enable stakeholders to access and share information about main and auxiliary engines, hydraulic pumps, and other valuable equipment. Additionally, the involvement of stakeholders in the design process ensured that the database satisfied their specific needs and requirements.

With maritime assets being particularly complex and costly, MAT offers stakeholders a data-driven methodology to optimise asset management strategies. Using the standardised database structure, stakeholders can make informed decisions regarding maintenance schedules, performance analysis, and cost-effective replacements for their maritime assets. This data-driven approach enhances overall efficiency and reduces the risk of unexpected breakdowns or downtime, ultimately leading to significant cost savings in the long run. As per a bridging strategy, listing vessels and valuable onboard components and tracking the equipment's specifications and condition information alone is a big step for the maritime industry. Therefore, this research focuses on a fundamental digital infrastructure design to bridge the gap in the sector.

An effective database design acts as the backbone to facilitate maritime circularity through material passports. The conceptual design of the database envisions the broad relationships among the various entities involved, including OEMs, component specs, physical onboard equipment, vessels, vessel owners, building and repairing shipyards, and ship recyclers. It sets the stage for defining what types of information should be stored and how they relate to one another. Figure 6-3 illustrates the entity-relationship diagrams for the database.

The logical design further refines this by specifying the database's tables, fields, and relationships, ensuring that data redundancy is minimised, and data integrity is maintained. For example, a 'Component Specs' table could contain properties such as component weight, dimensions, engine power, speed, emission level, etc. On the other hand, a 'Components' table could capture physical components from the real world with different serial numbers and potential different applications and link those back to the 'Component Specs' table. Figure 6-2 briefly defines tables, forms, queries, and reports, which form the overall structure. The logical design consists of various entity tables and relationships based on entity-relationship diagrams and converted to database tables (Zygiaris, 2018), as shown in Figure 6-4. In the maritime industry, building and repairing shipyards more often than not carry out both new building and repairing jobs interchangeably. Therefore, in the logical design, the same shipyards table represents both building shipyards and repairing shipyards. In the 'Vessels' table, it is reflected that a vessel can have different building and repairing shipyards.

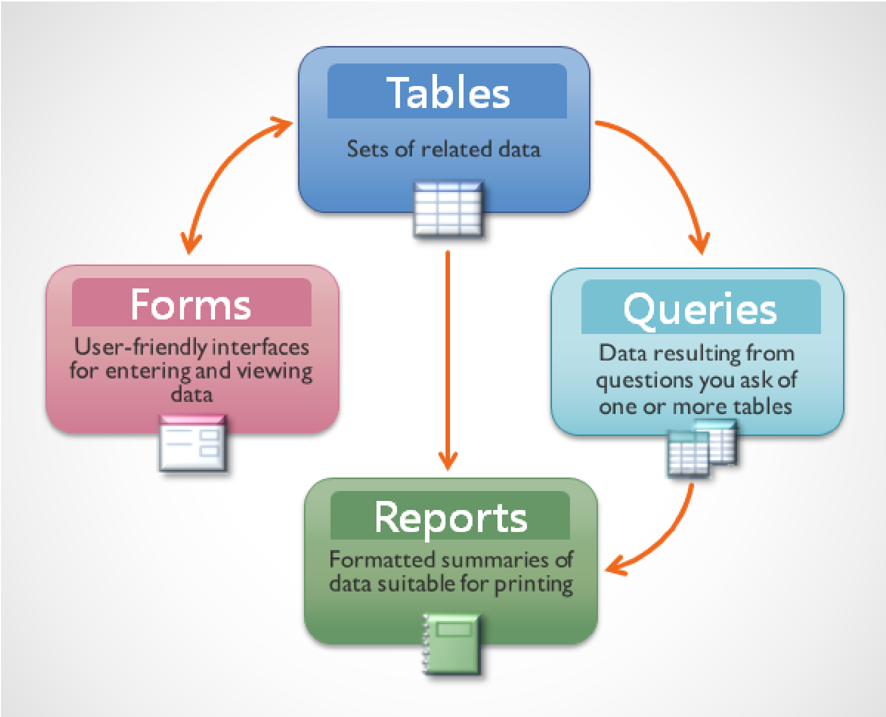


Figure 6-2: Basic database elements, from (GCF Global, 2013).

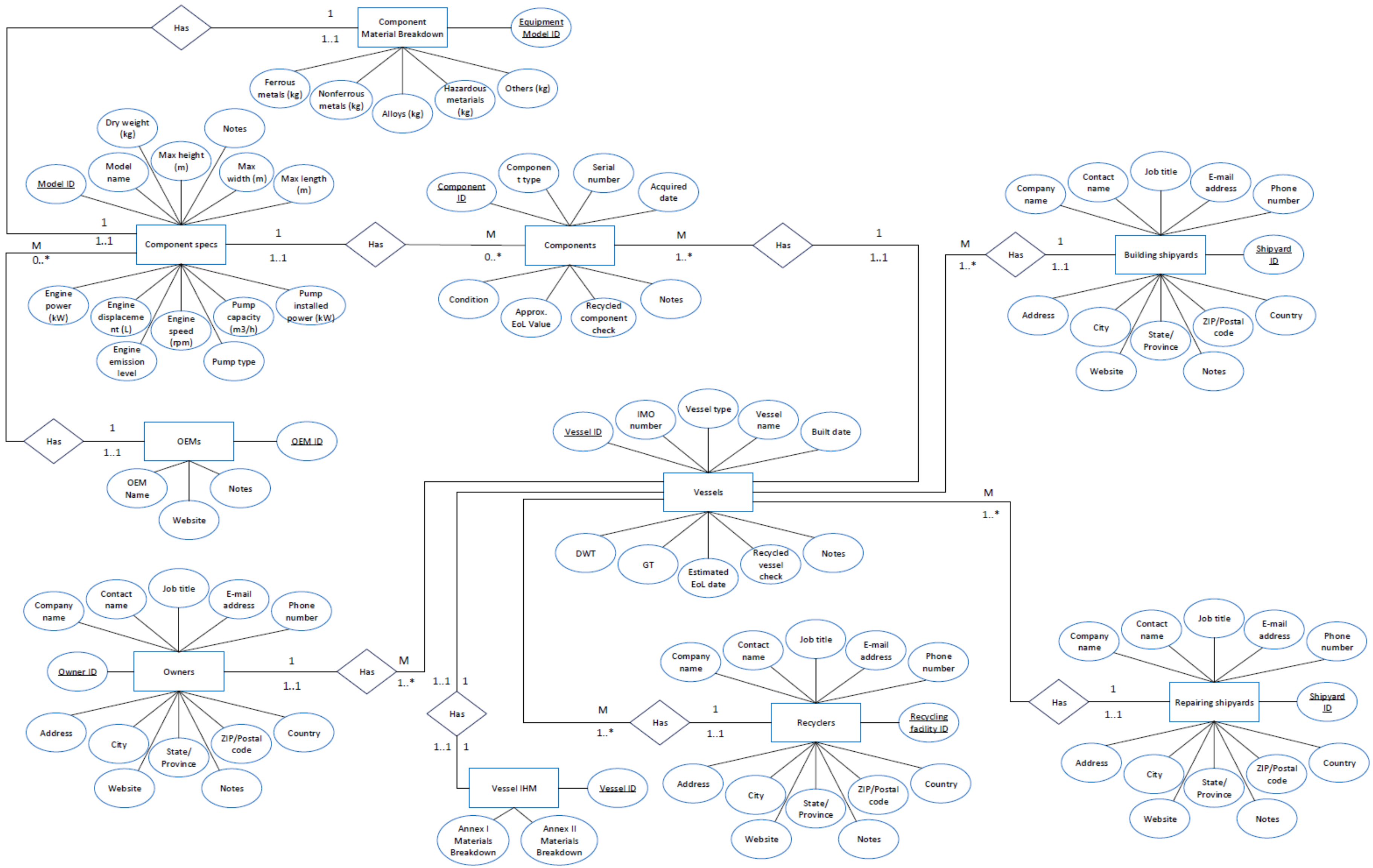


Figure 6-3: Entity-relationship chart.

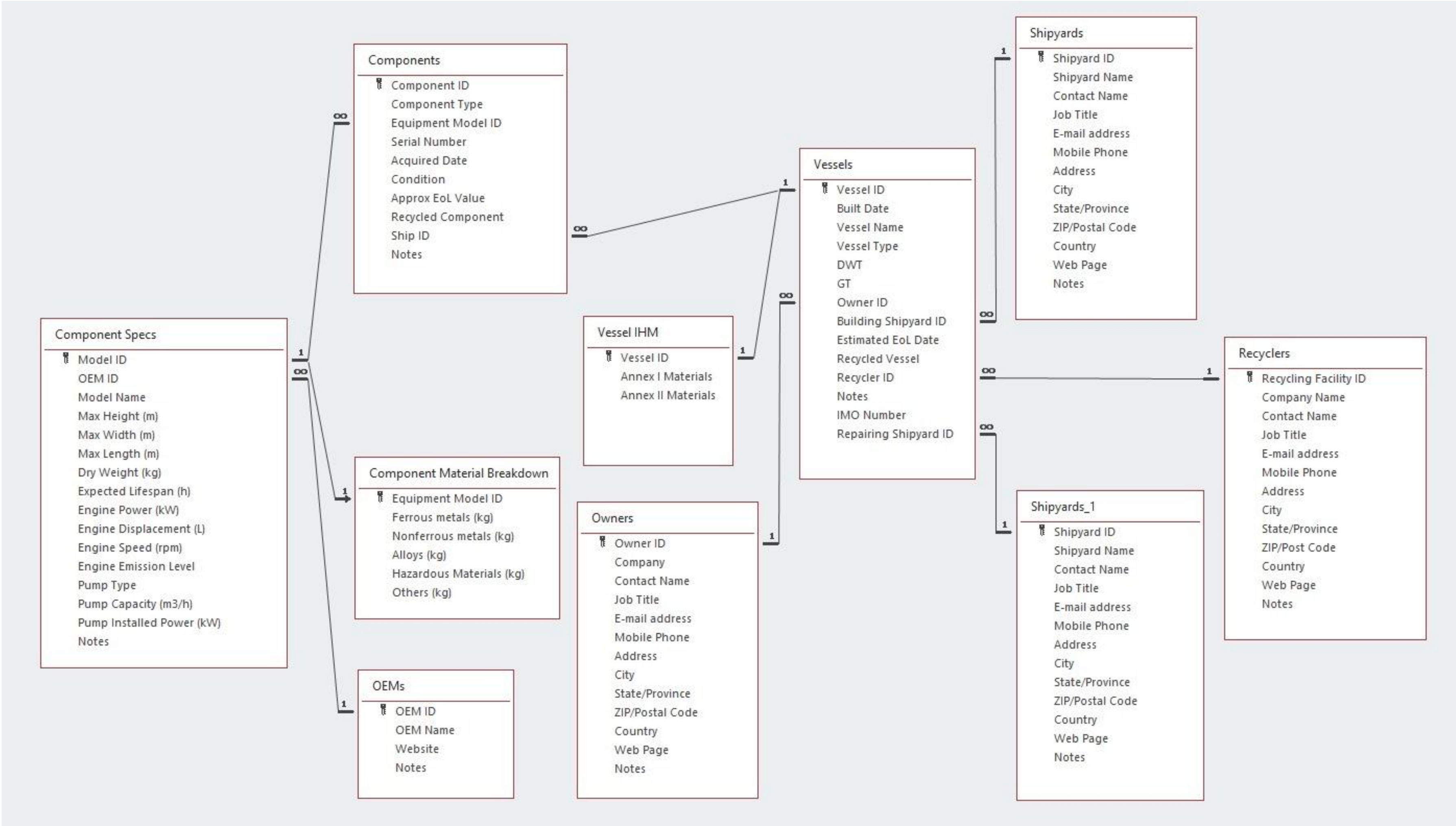


Figure 6-4: Logical database design.

Overall, there are nine unique tables in the suggested database: OEMs Table, Component Specs Table, Component Material Breakdown Table, Components Table, Owners Table, Shipyards Table, Recyclers Table, Vessels Table, and Vessels Inventory of Hazardous Materials (IHM) Table. Only the Shipyards Table and the Vessels Table have two connections between them, as the former provides shipyard data for building and repairing shipyards for vessels. The tables are introduced as follows:

- OEMs Table:

Like all tables in the database, this table contains its unique identification key (OEM ID). The table also stores information about maritime original equipment manufacturers, such as their names, websites, and general notes.

- Shipyards Table:

Building and/or repair shipyard data is stored in this table. This table assigns a Shipyard ID to each unique shipyard in the system and stores their name, contact person and contact information, address, web page, and general note information. As a specific case, the shipyard's table is connected to the vessel's table in two ways: the first connection feeds building shipyard information, while the second feeds repairing shipyard information. Most shipyards in the maritime industry can carry out both of these functions. A vessel is built in a known shipyard; however, the vessel can receive repair services in any other shipyard worldwide. Therefore, the repairing shipyard reflects the latest shipyard that conducted the repair work for that ship.

- Owners Table:

Shipowner or operator company data is stored in this table, such as contact information, including company name, contact name, position, e-mail, phone number, and corporate webpage.

- Recyclers Table:

Ship recycling facility or recycling shipyard data is stored here. This table contains similar contact information, addresses, web page details, and the free-text notes section. And it connects to the vessel's table.

- Components Table:

The components table is where each individual onboard engine and pump information for each vessel is recorded. This table combines the data from the Component Specs and Vessels tables, reaching all components of all ships registered in the database and their OEM specifications.

- Component Specs Table:

The component catalogue specifications for each unique equipment model should be recorded here by OEMs. These specifications include component dimensions (height, length, and width) and weight information, which are crucial for remanufacturing in transportation and material handling processes.

Since the database is designed for engines (main and auxiliary) and pumps within this study's scope, there is a standard component specification table for these two commodities. Therefore, each component model in this table should be filled with the engine or pump technical detail sections. Engine specs are power, displacement, speed, and emission standards, while pump specs are type (gear, centrifugal, etc.), capacity, and installed power. Apart from that, the table also contains a free-text notes section for each record.

- Component Material Breakdown Table:

The material breakdown table is added as a complementary to the component specifications table. They both store technical details of onboard components; however, the breakdown table is specifically dedicated to the material content of each piece of equipment, including ferrous metals, nonferrous metals, alloys, hazardous materials, and other substances. Therefore, this table falls within the responsibility of OEMs.

- Vessels Table:

The Vessels Table stores ships' data, such as their building shipyard, built date, vessel name, IMO number, vessel type, DWT, and GT data, and vessels are matched with their owners, up-to-date (latest) repairing shipyards, and optionally (if known) their final destination, e.g., ship recyclers. There are sections in this table for entering estimated end-of-life dates and indicators showing whether the ship is recycled or not.

- Vessels IHM Table:

This table is dedicated to the IHM, adopted in 2009 at the Hong Kong International Convention (HKC) for the safe and environmentally sound recycling of ships. The convention dictates that all vessels above 500 GT must create and keep updated IHM records (DNV, 2023; IMO, 2009). Moreover, European Regulation No. 1257/2013 on Ship Recycling (EU-SRR) aimed to facilitate early ratification of the HKC and raised the standards for EU-flagged vessels (ClassNK, 2023). Thus, this table has been added as a connection point so that the database can contain IHM records for each vessel or interact with any external IHM recording system that may develop in the future.

6.6.2 Stakeholder Accounts, Roles, and Responsibilities

For a MAT database to be effectively implemented and utilised, clearly defined stakeholder roles and responsibilities are imperative. In the context of the proposed database, these stakeholders include building and repairing shipyards, ship owners, OEMs, and ship recyclers. Each account type has varying access levels and responsibilities according to their organisation. In this system, an independent database management authority or administrator monitors the overall system, ensures smooth operation, and handles any errors. Ideally, the database administrator should be from a non-profit, unbiased organisation, such as IMO or academia. The involvement of an independent database administrator from a non-profit or unbiased organisation like IMO or academia helps ensure the integrity and impartiality of the system. On the other hand, academia may not be able to handle such things as ISO standards are not implemented. Possibly, recognised organisations such as classification societies can provide such services. The database administrator role is crucial in maintaining data accuracy, resolving conflicts, and addressing potential issues. The administrator can also provide guidance and support to stakeholders, ensuring they fully understand the system's functionalities and how to effectively utilise it for their specific needs.

Database tables were explained in the previous section above. Other instruments of a functional database are forms, queries, and reports, which are used for entering, viewing, and editing data for individual records, while reports present formatted summaries of data suitable for printing. Queries are the questions that users ask to single or multiple tables in the database, and queries can be used to produce reports as well. This section introduces the forms, queries, and reports that are essential tools for effective data management generated by this PhD research to cover all stakeholder groups. These tools allow stakeholders to interact with the database in a user-friendly manner, enabling them to input, retrieve, and analyse data efficiently.

6.6.2.1 Forms

In total, there are eight forms designed. Forms can constitute a basic interface for the database by allowing users to enter new records and view and edit existing data. The brief definitions of the forms are as follows:

- Owner/Operator Form is designed for entering and editing ship operator companies' corporate and contact information. It is connected to the Owner table in the database, and the database management authority should manage this information. And when needed, ship owners/operators should inform the database management authority of any update requirements regarding their information here. Figure 6-5 shows an empty Owner/Operator Form template below.

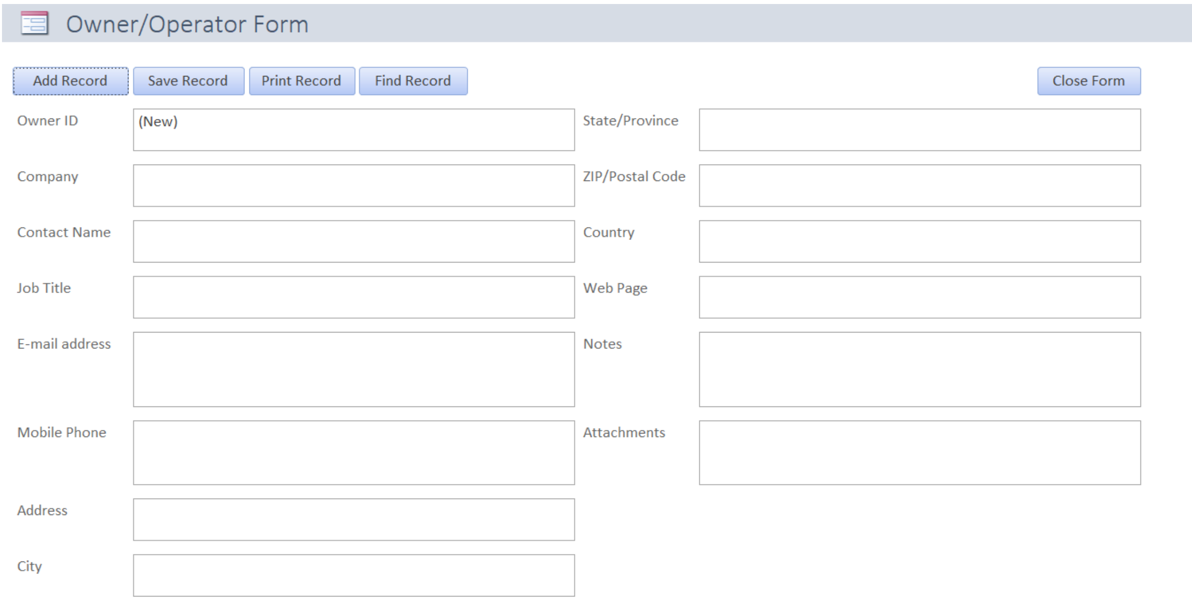


Figure 6-5: Template Owner/Operator Form.

- Shipyard Form is designed for entering and editing shipyards' corporate and contact information. It is connected to the Shipyards table in the database, and the database management authority should manage this information. When needed, shipyards should inform the database management authority of any update requirements regarding their information here. Figure 6-6 shows a Shipyard Form template.

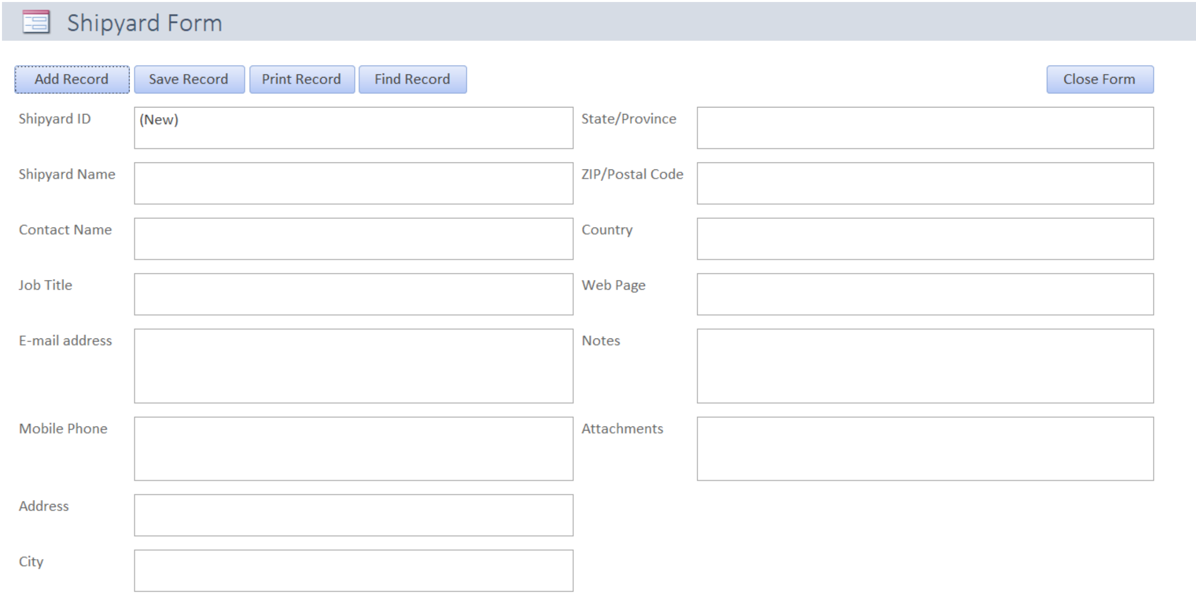


Figure 6-6: Template shipyard form.

- The Recycling Facility Form is designed for entering and editing recycling shipyards' or recyclers' corporate and contact information. It is connected to the Recyclers table in the database, and the database management authority should manage this information. Recycling companies should inform the database management authority of any update requirements regarding their information here when needed. Figure 6-7 shows an example of an empty Recycling Facility Form.

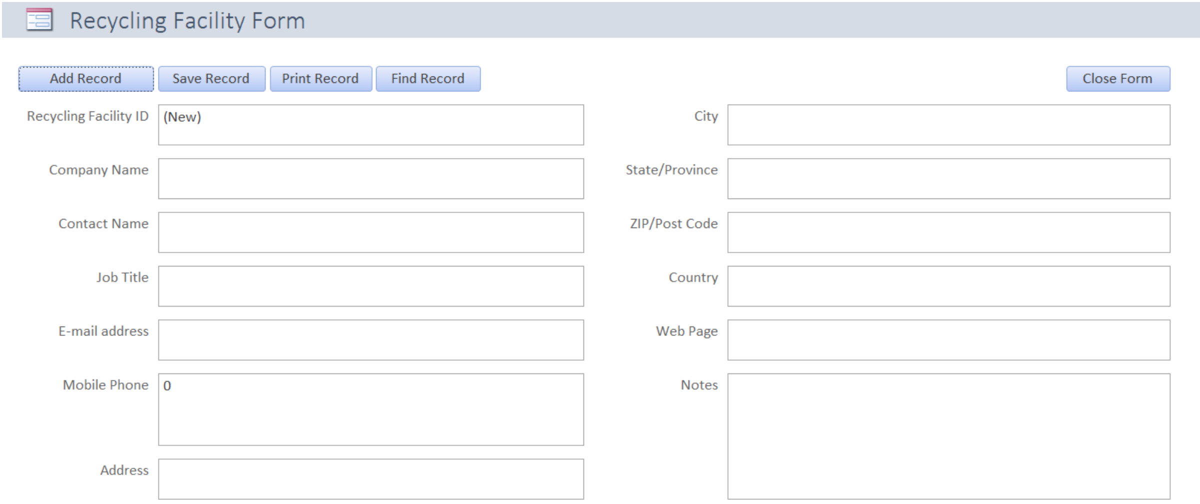


Figure 6-7: Template Recycling Facility Form.

- OEM Form is designed to enter and edit OEMs' corporate information. It is connected to the OEMs table in the database, and the database management authority should manage this information. When needed, OEMs should inform the database management authority of any update requirements regarding their information here. Figure 6-8 below presents an OEM Form template.

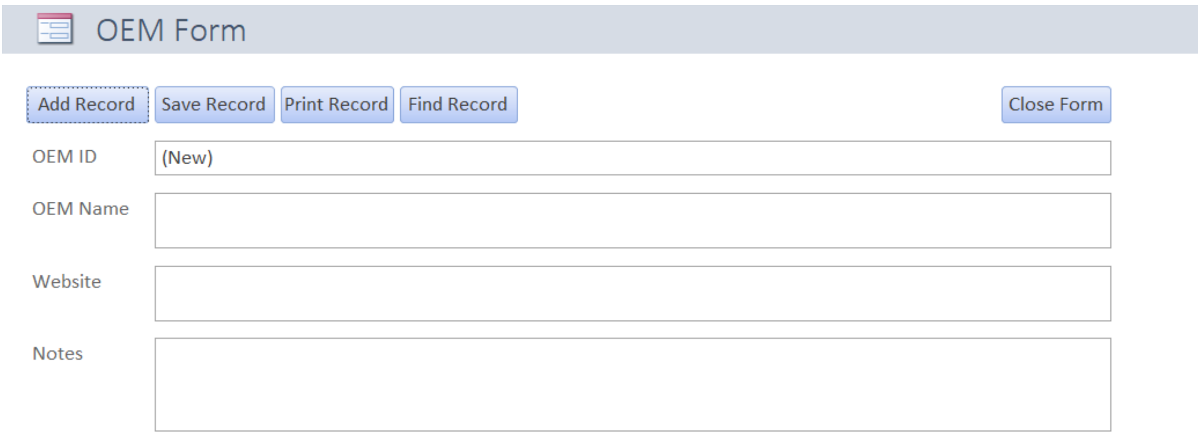


Figure 6-8: OEM Form template.

- Component Specification Form is connected to the Component Specs Table. In line with the database design, the main users of this form are OEMs. It is the OEM's responsibility to provide component specification data. Therefore, this form is designed mainly for OEM usage, and OEM data is called from the

OEM table. Thus, there is a drop-down list for selecting relevant OEMs on the upper right side of the form. Figure 6-9 shows the template form.

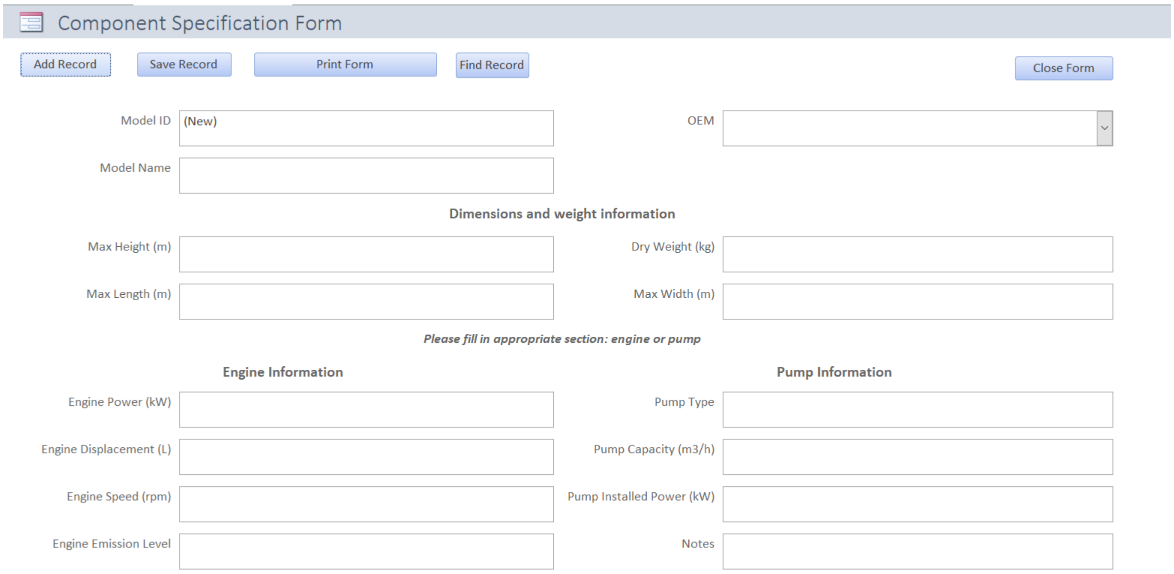


Figure 6-9: Component Specification Form template.

- The Component Material Breakdown Form is connected to the Component Material Breakdown Table. Similar to the previous form, OEMs use this form. The form should be filled out for each unique equipment model by its manufacturer, and the asset's dry weight should be split into ferrous metals, nonferrous metals, alloys, hazardous materials, and other substances. Figure 6-10 illustrates a component material breakdown form template (the material data is covered at this stage as it is not publicly available information).

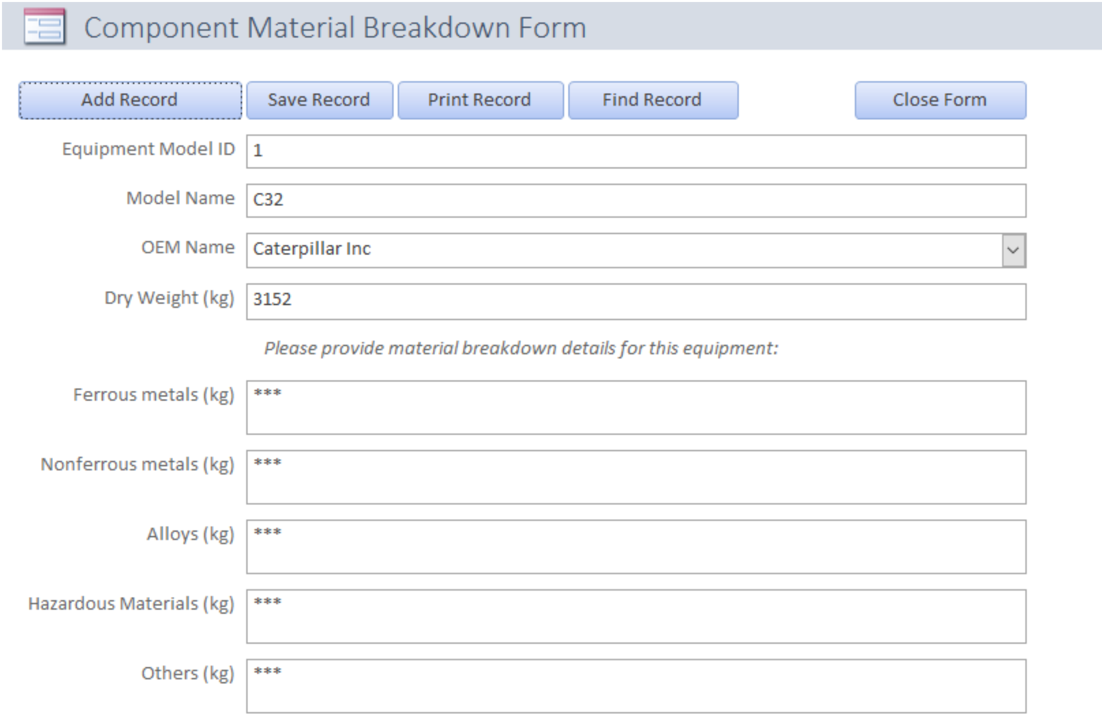


Figure 6-10: Component Material Breakdown template.

- Vessel Form is designed for entering and editing ships' technical (building shipyard, built date, type, GT, etc.), ownership, and recycling information. The form is connected to the Vessels table in the database, which also connects to Owners, Shipyards and Recyclers tables. Therefore, Building Shipyard, Repairing Shipyard, Owner and Recycling Facility elements of the form are designed as drop-down lists calling data from relevant tables. The vessel Type element is also a drop-down list of predefined ship types. Initially, the building shipyard should fill this form during a ship's building stage. The shipyard should create a record for the vessel by providing – at least – the information on the left-hand side of the form.

  The system automatically notifies shipowner organisations when a vessel is added, removed, or updated associated with their organisation. They can also query to see all the information about their ships. During the vessel's service time, ship owners or shipyards can update the ship's information if any changes happen. When the owner/operator enters or updates the repairing shipyard, the vessel's information becomes visible to the repairing yard. The database management authority should verify and approve them to keep the data updated.

The form also has an EoL part at the bottom right corner. Shipowners can enter an optional estimated EoL date or update it anytime. They can also specify a ship recycling facility if the recycling is planned. This will send the recycler a notification regarding their plan, and the recycler will then be able to see the vessel's information, including all equipment on board. Finally, when the ship is recycled, the recycler should check the Recycled Vessel box to indicate that decommissioning is complete. Figure 6-11 illustrates a Vessel Form template.

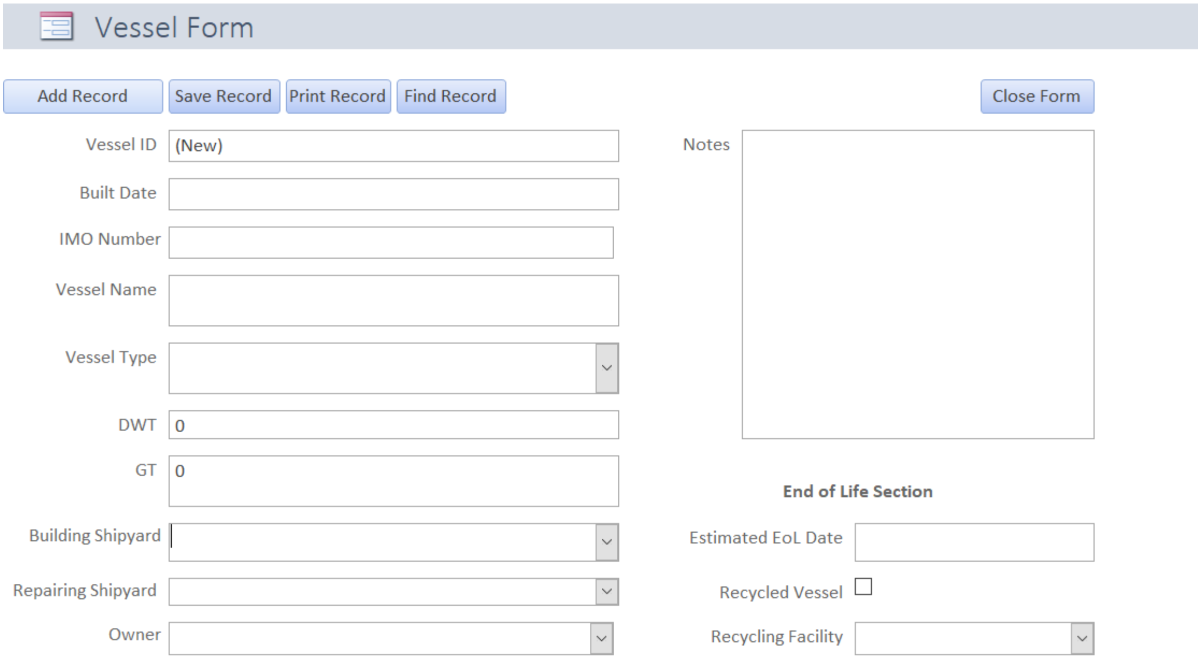


Figure 6-11: Template Vessel Form.

- On-Board Components Form (OBCF) is designed for adding, updating, or removing valuable components onboard vessels. The form is connected to the Components table in the database, with first-level connections between the Component Specs and Vessels tables. Thus, it is indirectly connected to all tables in the database. A pre-defined component type drop list indicates whether it is the main engine, an auxiliary engine, a pump, etc. Model and Ship selections are also designed as drop-down lists connected to their relevant

tables in the database. For instance, a vessel should be recorded in the database by submitting a Vessel Form first; only then can OBSF call that specific ship from the Vessels Table. Component serial number, acquisition date, condition, and approximate EoL value are other data managed by OBCF.
Like the Vessels Form, OBCF should first be filled in by shipyards during the shipbuilding phase. The shipyard should submit a form for each valuable component on board, such as main and auxiliary engines, pumps, etc. Then, the shipowner organisation is automatically notified by the system when a component is added, removed, or updated onboard a vessel associated with their organisation. They can also make a query to see all the components on board their ships. During the vessel's service time, ship owners or repairing shipyards can update the ship’s information if any changes happen. The database management authority should verify and approve them to keep the data updated.

Finally, when the component is removed from the vessel for recycling or remanufacturing purposes, the recycling facility or repairing shipyard should tick the *Recycled Component* box to indicate that the component is removed from the ship, and they are no longer associated. Figure 6-12 depicts an empty On-Board Components Form example.

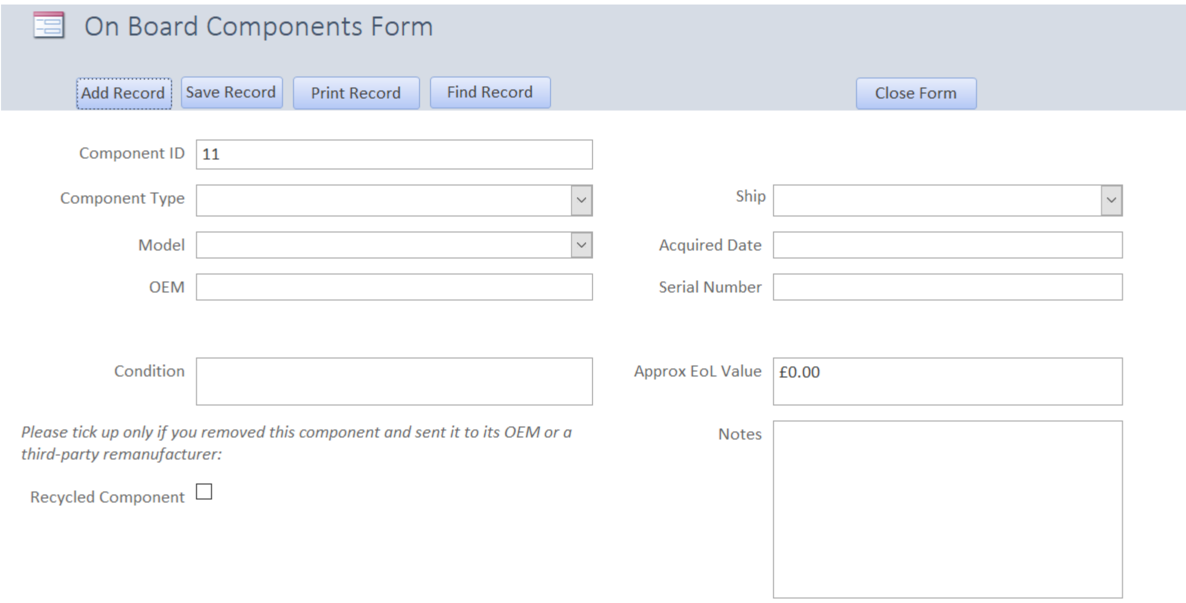


Figure 6-12: Empty onboard components form.

6.6.2.2 Queries and reports

While the forms explained in the previous section create data entry and editing interfaces, the database queries and reports allow the stakeholders to track vessels and components associated with their organisation regularly.

Within the scope of this study, some basic queries were written for the suggested database and are presented below. Structured Query Language (SQL) is used to write queries to communicate with the database. It is essential to underline that database queries are incredibly flexible tools that enable us to design tailor-made reports covering specific requirements. Therefore, apart from the queries shown below, any future report or function could be added later without any problem as long as the database includes that information.

Appendix B presents several queries written to provide valuable outputs for all stakeholder groups. Those queries are foundational examples of how the information stored in the database can be used; however, if any other information is needed, the database is capable of providing the requested information using SQL. The database management authority or administrator can create custom queries anytime and share their results with relevant stakeholder groups. Or, it can be converted to a standard report form and automated to produce regular reports that can be distributed to corresponding stakeholder accounts.

This section will provide sample query outputs and reports for each stakeholder group. The author hopes they help envisage the database's potential use and offer a glimpse of how the information can be utilised. These sample query outputs and reports can serve as a starting point for stakeholders to understand the possibilities and tailor their queries based on their specific needs. This might eventually end up with an extended database design for storing more detailed data or possible on-time condition monitoring functions. However, for now, this research focuses on the essential functions as a starting point. It sticks to its main purpose of tracking onboard engines and pumps on commercial vessels while causing the minimum workload to maritime stakeholders.

- Ship owner/operator:

Queries for ship owners or operators list the operating, recycled, and total assets (vessels and onboard equipment) associated with each ship owner. In other words, these queries show the data of the relevant assets for each particular shipowner organisation. Depending on their preference, the results will be shared with the owners regularly, such as weekly, biweekly, or monthly. Query 1 in Appendix B shows all components on board all vessels registered for "Ship Owner C", which includes the OEM name, component model, type, serial number, acquisition date, latest condition, approximate EoL value (if known), along with the vessel name and IMO number. In addition to these, two indicator columns show if the vessel and/or the components are recycled or decommissioned. Figure 6-13 shows the visual output of Query 1.

OEM Name	Model Name	Component Type	Serial Numbe	Acquired Date	Conditio	Approx EoL Value	IMO Numbe	Vessel Name	Company	Recycled Vessel	Recycled Com
Caterpillar Inc	C32	Auxiliary Engine	CAT000125	10/01/2022	Good	£0.00	9999999	Vessel C	Ship Owner C	☐	☐
MaK	8M 46 DF	Auxiliary Engine	CAT000123	10/01/2022	Good	£0.00	9999999	Vessel C	Ship Owner C	☐	☐
MaK	8M 46 DF	Main Engine	MAK00012346	10/01/2022	Good	£0.00	9999999	Vessel C	Ship Owner C	☐	☐
MaK	8M 46 DF	Main Engine	MAK00012345	10/01/2022	Good	£0.00	9999999	Vessel C	Ship Owner C	☐	☐
Lowara	Lowara NSCE 32-160/22/P25HCS4	Pump	LOWARA000434	10/01/2022	Good	£0.00	9999999	Vessel C	Ship Owner C	☐	☐
Lowara	Lowara NSCE 32-160/22/P25HCS4	Pump	LOWARA00123	10/01/2022	Good	£0.00	9999999	Vessel C	Ship Owner C	☐	☐
Caterpillar Inc	C32	Auxiliary Engine	CAT00650	10/01/2013	Good	£0.00	8888888	Vessel D	Ship Owner C	☐	☐
Caterpillar Inc	C32	Auxiliary Engine	CAT00651	10/01/2013	Good	£0.00	8888888	Vessel D	Ship Owner C	☐	☐
Wartsila	Wartsila 16V46F	Main Engine	WME100202	10/01/2013	Good	£0.00	8888888	Vessel D	Ship Owner C	☐	☐
Wartsila	Wartsila 16V46F	Main Engine	WME100201	10/01/2013	Good	£0.00	8888888	Vessel D	Ship Owner C	☐	☐
Caterpillar Inc	C18	Auxiliary Engine	CAT010901	01/01/2010	Good	£0.00	6985698	Vessel E	Ship Owner C	☐	☐
Caterpillar Inc	C18	Auxiliary Engine	CAT010900	01/01/2010	Good	£0.00	6985698	Vessel E	Ship Owner C	☐	☐
Caterpillar Inc	C32	Main Engine	CAT00183	01/01/2010	Good	£0.00	6985698	Vessel E	Ship Owner C	☐	☐
Caterpillar Inc	C32	Main Engine	CAT00185	01/01/2010	Good	£0.00	6985698	Vessel E	Ship Owner C	☐	☐
*										▣	▣

Figure 6-13: Output of Query 1 for ship owners / operators.

On the other hand, Query 2 gathers information about the vessels belonging to "Ship Owner C" and shows vessel name, IMO number, GT, DWT, built date, building shipyard, latest repairing shipyard, recycling yard (shows as TBD—to be determined if not specified), and estimated EoL date (if entered). Figure 6-14 depicts a report sample created using Microsoft Access as the query's output. Similarly, Query 3 is used to provide onboard equipment dimensions and dry weights along with basic vessel and component information for "Ship Owner C" as shown in Figure 6-15.

Vessel-shipyard-recycler report for ship owners / operators

16 October 2023

Ship Owner/Operator	Vessel Name	IMO Number	GT	DWT	Built Date	Building Shipyard	Repairing Shipyard	Recycling Yard	Estimated EoL Date	Notes
Ship Owner C	Vessel C	9999999	3200	4500	03/01/2022	Shipyard A	Shipyard C	TBD	01/01/2047	
Ship Owner C	Vessel D	8888888	71112	80228	28/04/2013	Shipyard A	Shipyard B	TBD	28/04/2049	
Ship Owner C	Vessel E	6985698	644	50	12/06/2010	Shipyard A	Shipyard C	TBD	30/12/2045	
3										

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Figure 6-14: Output of Query 2 for ship owners/operators in report format.

Onboard Equipment Report for Ship Owners / Operators

16 October 2023
14:00:03

Vessel Name	IMO Number	Building Shipyard	Repairing Shipyard	Component Type	Serial Number	Acquired Date	Condition	Approx EoL Value	OEM Name	Model Name	Max Height (m)	Max Width (m)	Max Length (m)	Dry Weight (kg)
Vessel C	9999999	Shipyard A	Shipyard C	Main Engine	MAK00012345	10/01/2022	Good	£0.00	MaK	8M 46 DF	5.5	2.961	9.8	114000
Vessel C	9999999	Shipyard A	Shipyard C	Auxiliary Engine	CAT000123	10/01/2022	Good	£0.00	MaK	8M 46 DF	5.5	2.961	9.8	114000
Vessel D	8888888	Shipyard A	Shipyard B	Main Engine	WME100201	10/01/2013	Good	£0.00	Wartsila	Wartsila 16V46F	5.863	4.678	12.871	233000
Vessel C	9999999	Shipyard A	Shipyard C	Auxiliary Engine	CAT000125	10/01/2022	Good	£0.00	Caterpillar Inc	C32	1.59	1.53	2.13	3152
Vessel C	9999999	Shipyard A	Shipyard C	Pump	LOWARA00123	10/01/2022	Good	£0.00	Lowara	Lowara NSCE 32-160/22/P25HCS4	0.30	0.25	0.55	45
Vessel C	9999999	Shipyard A	Shipyard C	Pump	LOWARA000434	10/01/2022	Good	£0.00	Lowara	Lowara NSCE 32-160/22/P25HCS4	0.30	0.25	0.55	45
Vessel D	8888888	Shipyard A	Shipyard B	Auxiliary Engine	CAT00651	10/01/2013	Good	£0.00	Caterpillar Inc	C32	1.59	1.53	2.13	3152
Vessel D	8888888	Shipyard A	Shipyard B	Auxiliary Engine	CAT00650	10/01/2013	Good	£0.00	Caterpillar Inc	C32	1.59	1.53	2.13	3152
Vessel C	9999999	Shipyard A	Shipyard C	Main Engine	MAK00012346	10/01/2022	Good	£0.00	MaK	8M 46 DF	5.5	2.961	9.8	114000
Vessel D	8888888	Shipyard A	Shipyard B	Main Engine	WME100202	10/01/2013	Good	£0.00	Wartsila	Wartsila 16V46F	5.863	4.678	12.871	233000
Vessel E	6985698	Shipyard A	Shipyard C	Main Engine	CAT00185	01/01/2010	Good	£0.00	Caterpillar Inc	C32	1.59	1.53	2.13	3152
Vessel E	6985698	Shipyard A	Shipyard C	Main Engine	CAT00183	01/01/2010	Good	£0.00	Caterpillar Inc	C32	1.59	1.53	2.13	3152
Vessel E	6985698	Shipyard A	Shipyard C	Auxiliary Engine	CAT010900	01/01/2010	Good	£0.00	Caterpillar Inc	C18	1.648	1.411	3.038	1750
Vessel E	6985698	Shipyard A	Shipyard C	Auxiliary Engine	CAT010901	01/01/2010	Good	£0.00	Caterpillar Inc	C18	1.648	1.411	3.038	1750
								£0.00						

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Figure 6-15: Output of Query 3 for ship owners/operators in report format.

- Building Shipyards:

Query 4 is a dedicated query for building shipyards. It lists all built vessels and their components. Figure 6-16 shows the outputs of Query 4 for "Shipyard A" in a standard report format using dummy inputs. In this way, ship building yards can see all the vessels they have built with their onboard component information.

- Repair Shipyards:

Unlike the building shipyards, the repairing shipyards have two different queries; the first contains vessel data, including owner and building shipyard contact info, while the other contains on-board equipment information for each vessel. Queries 5 and 6 represent vessel data and component data for "Shipyard C" as an example from our dummy database, and the outputs are shown in Figure 6-17 and Figure 6-18, respectively.

Assets Report for Building Shipyards 16 October 2023

Building Shipyard	Vessel Type	Vessel Name	IMO Number	GT	DWT	Component Type	OEM	Component Model	Component Serial No
Shipyard A	General Cargo	Vessel C	9999999	3200	4500	Main Engine	MaK	8M 46 DF	MAK00012345
Shipyard A	General Cargo	Vessel C	9999999	3200	4500	Auxiliary Engine	MaK	8M 46 DF	CAT000123
Shipyard A	Container Ship	Vessel D	8888888	71112	80228	Main Engine	Wartsila	Wartsila 16V46F	WME100201
Shipyard A	General Cargo	Vessel C	9999999	3200	4500	Auxiliary Engine	Caterpillar Inc	C32	CAT000125
Shipyard A	General Cargo	Vessel C	9999999	3200	4500	Pump	Lowara	Lowara NSCE 32-160/22/P25HCS4	LOWARA00123
Shipyard A	General Cargo	Vessel C	9999999	3200	4500	Pump	Lowara	Lowara NSCE 32-160/22/P25HCS4	LOWARA000434
Shipyard A	Ro-Ro	Vessel B	7429669	18000	1000	Main Engine	Caterpillar Inc	C32	CAT00441
Shipyard A	Ro-Ro	Vessel B	7429669	18000	1000	Main Engine	Caterpillar Inc	C32	CAT00442
Shipyard A	Ro-Ro	Vessel B	7429669	18000	1000	Main Engine	Caterpillar Inc	C32	CAT00443
Shipyard A	Ro-Ro	Vessel B	7429669	18000	1000	Main Engine	Caterpillar Inc	C32	CAT00444
Shipyard A	Container Ship	Vessel D	8888888	71112	80228	Auxiliary Engine	Caterpillar Inc	C32	CAT00651
Shipyard A	Container Ship	Vessel D	8888888	71112	80228	Auxiliary Engine	Caterpillar Inc	C32	CAT00650
Shipyard A	General Cargo	Vessel C	9999999	3200	4500	Main Engine	MaK	8M 46 DF	MAK00012346
Shipyard A	Container Ship	Vessel D	8888888	71112	80228	Main Engine	Wartsila	Wartsila 16V46F	WME100202
Shipyard A	Passenger Ship	Vessel E	6985698	644	50	Main Engine	Caterpillar Inc	C32	CAT00185
Shipyard A	Passenger Ship	Vessel E	6985698	644	50	Main Engine	Caterpillar Inc	C32	CAT00183
Shipyard A	Passenger Ship	Vessel E	6985698	644	50	Auxiliary Engine	Caterpillar Inc	C18	CAT010900
Shipyard A	Passenger Ship	Vessel E	6985698	644	50	Auxiliary Engine	Caterpillar Inc	C18	CAT010901

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Figure 6-16: Onboard assets report for building shipyards (Query 4).

Vessels Report for Repairing Shipyards 16 October 2023

Repairing Shipyard	Vessel Name	Vessel Type	DWT	GT	Ship Owner/Operator	Owners Contact	Owners Contact Tel	Owners Contact E-mail	Building Shipyard	Building Shipyard Contact	Building Shipyard Tel	Building Shipyard E-mail
Shipyard C	Vessel B	Ro-Ro	1000	18000	Ship Owner A	Owner contact A	123456789	shipownerA@example.com	Shipyard A	Shipyard contact A	12349875	shipyardcontactA@example.com
Shipyard C	Vessel C	General Cargo	4500	3200	Ship Owner C	Owner Contact C	+44 1234 567890	shipownerC@example.com	Shipyard A	Shipyard contact A	12349875	shipyardcontactA@example.com
Shipyard C	Vessel E	Passenger Ship	50	644	Ship Owner C	Owner Contact C	+44 1234 567890	shipownerC@example.com	Shipyard A	Shipyard contact A	12349875	shipyardcontactA@example.com

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Figure 6-17: Vessels report for repairing shipyards (Query 5).

On-board Components Report for Repairing Shipyards 24 December 2023

Repairing Shipyard	Vessel Name	Component Type	Component OEM	Component Model	Max Height(m)	Max Width(m)	Max Length(m)	Dry Weight(kg)	Component Serial Number	Acquired Date	Condition	Approx EoL Value	Notes	Recycled Component
Shipyard C	Vessel B	Main Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00444	01/01/2010	good	£0.00	main engine 4/4	☐
Shipyard C	Vessel B	Main Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00443	01/01/2010	good	£0.00	main engine 3/4	☐
Shipyard C	Vessel B	Main Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00442	01/01/2010	good	£0.00	main engine 2/4	☐
Shipyard C	Vessel B	Main Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00441	01/01/2010	good	£0.00	main engine 1/4	☐
Shipyard C	Vessel C	Auxiliary Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT000125	10/01/2022	Good	£0.00	2rd aux engine	☐
Shipyard C	Vessel C	Auxiliary Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT000123	10/01/2022	Good	£0.00	1st aux engine	☐
Shipyard C	Vessel C	Main Engine	MaK	8M 46 DF	5.5	2.961	9.8	114000	MAK00012346	10/01/2022	Good	£0.00		☐
Shipyard C	Vessel C	Main Engine	MaK	8M 46 DF	5.5	2.961	9.8	114000	MAK00012345	10/01/2022	Good	£0.00		☐
Shipyard C	Vessel C	Pump	Lowara	Lowara NSCE 32-160/22/P25HCS4	0.30	0.25	0.55	45	LOWARA000434	10/01/2022	Good	£0.00	2nd ballast pump	☐
Shipyard C	Vessel C	Pump	Lowara	Lowara NSCE 32-160/22/P25HCS4	0.30	0.25	0.55	45	LOWARA00123	10/01/2022	Good	£0.00	1st ballast pump	☐
Shipyard C	Vessel E	Auxiliary Engine	Caterpillar Inc	C18	1.648	1.411	3.038	1750	CAT010901	01/01/2010	Good	£0.00	2nd aux engine	☐
Shipyard C	Vessel E	Auxiliary Engine	Caterpillar Inc	C18	1.648	1.411	3.038	1750	CAT010900	01/01/2010	Good	£0.00	1st aux engine	☐
Shipyard C	Vessel E	Main Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00183	01/01/2010	Good	£0.00	2nd main engine	☐
Shipyard C	Vessel E	Main Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00185	01/01/2010	Good	£0.00	1st main engine	☐

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Figure 6-18: Onboard components report for ship repair yards (Query 6).

- Ship Recyclers:

Four separate queries have been written for ship recycling facilities. The first one (Query 7 in Appendix B) is focused on vessels assigned to the particular ship recycler and shows vessel information such as their name, IMO number, type, GT, DWT, built date, owner company, owner contact information, and notes. Query 8 dives into the on-board engine details on these vessels, while Query 9 illustrates on-board pump information. The former depicts engine specifications such as power, displacement, and speed, and the latter presents pump specs on top of common dimension and weight information for each component. Lastly, Query 11 is dedicated to the material breakdown of onboard components. Figure 6-19 and Figure 6-20 demonstrate the vessel and the onboard engine reports for "Recycling Facility B" as examples, while Figure 6-21 presents the material breakdown of onboard assets for the same recycling facility.

Vessels Report for Ship Recyclers

16 October 2023

Recycler	Vessel Name	IMO Number	Vessel Type	GT	DWT	Built Date	Company	Contact Name	E-mail address	Mobile Phone	Notes
Recycling Facility B	Vessel A	8935677	Tanker	15697	27000	01/01/2006	Ship Owner B	Owner contact B	shipownerB@example.com	999-232-111-22-33	
Recycling Facility B	Vessel B	7429669	Ro-Ro	18000	1000	01/01/1975	Ship Owner A	Owner contact A	shipownerA@example.com	123456789	Vessel refitted in 2010.

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Figure 6-19: Vessels report for ship recyclers (Query 7).

On-board Engines Report for Ship Recyclers

16 October 2023

Recycler	Vessel Name	Component Type	Component OEM	Component Model	Max Height	Max Width	Max Length	Dry Weight	Component Serial Number	Component Acquired	Componen t Condition	Engine Power	Engine Displacement	Engine Speed
Recycling Facility B	Vessel A	Main Engine	Wartsila	Wartsila 16V46F	5.863	4.678	12.871	233000	WRT00723	01/01/2000	end-of-life	19200	1542	600
Recycling Facility B	Vessel A	Auxiliary Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00797	01/01/2000	end-of-life	1342	32.1	2300
Recycling Facility B	Vessel A	Auxiliary Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00798	01/01/2000	End-of-life	1342	32.1	2300
Recycling Facility B	Vessel A	Auxiliary Engine	Volvo Penta	D16 MH	1.58	1.05	1.82	1750	VLVPNT0088812	01/01/2012	good	551	16.1	1900
Recycling Facility B	Vessel B	Main Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00441	01/01/2010	good	1342	32.1	2300
Recycling Facility B	Vessel B	Main Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00442	01/01/2010	good	1342	32.1	2300
Recycling Facility B	Vessel B	Main Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00443	01/01/2010	good	1342	32.1	2300
Recycling Facility B	Vessel B	Main Engine	Caterpillar Inc	C32	1.59	1.53	2.13	3152	CAT00444	01/01/2010	good	1342	32.1	2300

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Figure 6-20: Onboard engines report for ship recyclers (Query 8).

Onboard Equipment Material Breakdown Report for Ship Recyclers

14 December 2023

Company Name	Vessel Name	Component Type	OEM Name	Model Name	Dry Weight (kg)	Ferrous metals (kg)	Nonferrous metals (kg)	Alloys (kg)	Hazardous Materials (kg)	Others (kg)
Recycling Facility B	Vessel A	Main Engine	Wartsila	Wartsila 16V46F	233000	***	***	***	***	***
Recycling Facility B	Vessel A	Auxiliary Engine	Caterpillar Inc	C32	3152	***	***	***	***	***
Recycling Facility B	Vessel A	Auxiliary Engine	Caterpillar Inc	C32	3152	***	***	***	***	***
Recycling Facility B	Vessel A	Auxiliary Engine	Volvo Penta	D16 MH	1750	***	***	***	***	***
Recycling Facility B	Vessel B	Main Engine	Caterpillar Inc	C32	3152	***	***	***	***	***
Recycling Facility B	Vessel B	Main Engine	Caterpillar Inc	C32	3152	***	***	***	***	***
Recycling Facility B	Vessel B	Main Engine	Caterpillar Inc	C32	3152	***	***	***	***	***
Recycling Facility B	Vessel B	Main Engine	Caterpillar Inc	C32	3152	***	***	***	***	***

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Figure 6-21: Onboard equipment material breakdown report for ship recyclers (Query 11)

- OEMs:

A single query is created for OEMs to enable them to track all their components onboard entire vessels in the database. Query 10 represents an example of a "Caterpillar" branded components query from the dummy database, and Figure 6-22 displays its output in a straightforward report format.

On-board Equipment Report for OEMs

16 October 2023

OEM	Component Model	Component S/N	Vessel Name	Vessel Type	Component Type	Estimated EoL Date	Ship Owner/Operato	Owner Contact Name	Owner Contact E-mail address	Owner Contact Tel	Recycling Shipyard	Recycler Contact Name	Recycler Contact E-mail address	Recycler Contact Tel.
Caterpillar Inc	C32	CAT000123	Vessel C	General Cargo	Auxiliary Engine	01/01/2047	Ship Owner C	Owner Contact C	shipownerC@example.com	+44 1234 567890	TBD			
Caterpillar Inc	C32	CAT000125	Vessel C	General Cargo	Auxiliary Engine	01/01/2047	Ship Owner C	Owner Contact C	shipownerC@example.com	+44 1234 567890	TBD			
Caterpillar Inc	C32	CAT00797	Vessel A	Tanker	Auxiliary Engine	20/01/2022	Ship Owner B	Owner contact B	shipownerB@example.com	999-232-111-22-33	Recycling Facility B	Recycling Contact B	recyclerB@example.com	123456789
Caterpillar Inc	C32	CAT00798	Vessel A	Tanker	Auxiliary Engine	20/01/2022	Ship Owner B	Owner contact B	shipownerB@example.com	999-232-111-22-33	Recycling Facility B	Recycling Contact B	recyclerB@example.com	123456789
Caterpillar Inc	C32	CAT00441	Vessel B	Ro-Ro	Main Engine	01/01/2025	Ship Owner A	Owner contact A	shipownerA@example.com	123456789	Recycling Facility B	Recycling Contact B	recyclerB@example.com	123456789
Caterpillar Inc	C32	CAT00442	Vessel B	Ro-Ro	Main Engine	01/01/2025	Ship Owner A	Owner contact A	shipownerA@example.com	123456789	Recycling Facility B	Recycling Contact B	recyclerB@example.com	123456789
Caterpillar Inc	C32	CAT00443	Vessel B	Ro-Ro	Main Engine	01/01/2025	Ship Owner A	Owner contact A	shipownerA@example.com	123456789	Recycling Facility B	Recycling Contact B	recyclerB@example.com	123456789
Caterpillar Inc	C32	CAT00444	Vessel B	Ro-Ro	Main Engine	01/01/2025	Ship Owner A	Owner contact A	shipownerA@example.com	123456789	Recycling Facility B	Recycling Contact B	recyclerB@example.com	123456789
Caterpillar Inc	C32	CAT00651	Vessel D	Container Ship	Auxiliary Engine	28/04/2049	Ship Owner C	Owner Contact C	shipownerC@example.com	+44 1234 567890	TBD			
Caterpillar Inc	C32	CAT00650	Vessel D	Container Ship	Auxiliary Engine	28/04/2049	Ship Owner C	Owner Contact C	shipownerC@example.com	+44 1234 567890	TBD			
Caterpillar Inc	C32	CAT00185	Vessel E	Passenger Ship	Main Engine	30/12/2045	Ship Owner C	Owner Contact C	shipownerC@example.com	+44 1234 567890	TBD			
Caterpillar Inc	C32	CAT00183	Vessel E	Passenger Ship	Main Engine	30/12/2045	Ship Owner C	Owner Contact C	shipownerC@example.com	+44 1234 567890	TBD			
Caterpillar Inc	C18	CAT010900	Vessel E	Passenger Ship	Auxiliary Engine	30/12/2045	Ship Owner C	Owner Contact C	shipownerC@example.com	+44 1234 567890	TBD			
Caterpillar Inc	C18	CAT010901	Vessel E	Passenger Ship	Auxiliary Engine	30/12/2045	Ship Owner C	Owner Contact C	shipownerC@example.com	+44 1234 567890	TBD			

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Figure 6-22: Onboard equipment report for OEMs (Query 10).

6.6.3 Database Validation Workshop

The validation workshop, held at the University of Strathclyde, aimed to introduce the maritime database to experts from different stakeholder groups. Twelve highly experienced professionals (three per each stakeholder group) participated in the workshop: ship owners, original equipment manufacturers, shipyards (new build or repair), and ship recycling facilities. These experts were selected based on their extensive knowledge and involvement in the maritime industry, ensuring that their assessments would be valuable and representative of the end-users' perspective. Appendix B includes the background and expertise of the participants.

The expert opinion scores collected from maritime experts play a crucial role in evaluating the database's performance. These scores provide valuable insights into the tool's functionality, simplicity, and long-term potential benefits. Using a 1–5 Likert scale, the experts rated the database based on its usefulness, ease of use, and potential benefits. These scores serve as quantitative indicators of the experts' perceptions and can be used to identify areas of improvement or strengths in the database's design and functionality. Table 6-1 shows expert opinion scores in these three dimensions, the current state of corresponding maritime stakeholders and the potential impacts discussed during the validation workshops.

Table 6-1: Expert opinion scores for database validation.

Maritime Stakeholder Group	Industry's Current State According to Previous Workshops	Developed Tool's Impact on Future Maritime Industry	Expert Opinion (1 – 5 rating)		
			Functionality score (usefulness)	Ease of use score (simplicity)	Long-term potential benefits
Ship Owner	Are eager to estimate EoL value of their assets more accurately. CE knowledge level is an important improvement area.	Will boost the availability of RRR products. More accurate EoL value estimation for marine assets.	4.33	4.67	4.33
Shipyard	Are willing to participate in circular economy principles, however suffering from lack of awareness and demand in the industry.	Will become core-component suppliers for OEMs and other remanufacturers. Will be able to offer RRR products to their customers.	4	4.33	4.33
OEM	Are able to carry out advanced CE principles, but there are fundamental barriers such as poor reverse supply chain and low industry awareness towards CE.	Will benefit from the transparency and traceability of their equipment in the industry. Will be able to reach many more core parts needed for remanufacturing operations.	4.67	4.67	5.00
Recycling Facility	Utilising their own networks to make use of EoL equipment onboard. Very much interested in becoming suppliers of core components for OEMs and 3rd party remanufacturers.	Will become the main core-component suppliers for OEMs and other remanufacturers. Will be able to precisely estimate decommissioning value of ships.	4.33	4.33	4.67

During the workshop, experts had the opportunity to interact with the database and receive sample reports. As a result, they provided valuable feedback, which was used to amend database tables, add new columns, and update forms and reports. One expert from a shipyard stakeholder highlighted the database's quick and hassle-free asset creation and updating functions, stating that it would not significantly increase their workload to add or amend data for the vessels they service. Another expert from an OEM stakeholder highlighted that the database's detailed coverage of marine assets on the existing merchant fleet would help drive advanced CE applications such as remanufacturing forward in the maritime industry. Ultimately, the database would foster innovation and collaboration within the industry by providing a centralised platform for sharing crucial information regarding the reverse supply chain and increasing transparency in the sector. These discussions shed light on the far-reaching benefits the database can bring to the maritime sector.

6.7 Case Study on Financial Benefits

This section presents a case study for an example vessel to demonstrate the potential benefits of the tool and the circular economy practices it will promote in the maritime domain. The ship owner of the case study vessel is one of the experts who participated in the database validation workshop in the previous section.

The case study presented in this section intentionally selected a vessel with a smaller gross tonnage (GT) than the world average to stay on the safe side in the generalisation steps in the following steps. The average world fleet of 105,395 commercial vessels is 14,581 gross tonnes (GT) (UNCTADstat, 2023), while the case study vessel has 8525 GT. The total fleet contains ultra-large ships, such as ultra-large crude carriers (ULCC) or very large ore carriers (VLOC), with capacities exceeding 230,000 GT. These ultra-large ships can significantly elevate the world average and could potentially distort the study results. Therefore, the author tried to prevent the presence of ultra-large ships in the entire fleet from skewing their findings and conclusions by choosing a vessel with the most common smaller GT.

The case study consists of six steps, as follows:

- Step1:

The ship owner company created a new record to enter the vessel into the database using the vessel form shown in Figure 6-23. The vessel's IMO number is hidden for confidentiality purposes; also, instead of its real name, Vessel H is used for the case study.

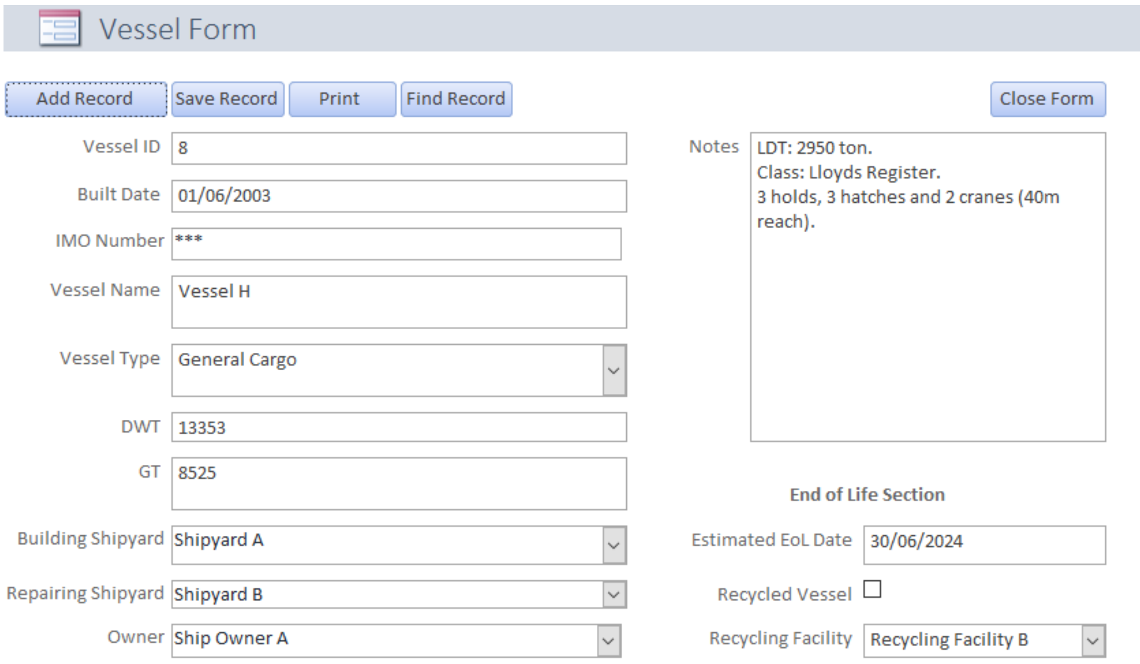

Figure 6-23: Entering the vessel into the database.

- Step 2:

Then, the ship owner created onboard equipment records for the main and auxiliary machinery. The vessel's first engineer and the latest shipyard in which the vessel had been dry-docked provided engine hours both current and during the last major overhaul records, as presented in Figure 6-24.

Case Study - Onboard Component Details on Vessel H

15 December 2023

Vessel Name	Component Type	OEM Name	Model Name	Max Height (m)	Max Width (m)	Max Length (m)	Dry Weight (kg)	Serial Number	Acquired Date	Condition	Engine Power (kW)	Engine Displacement (L)	Engine Speed (rpm)	Engine Emission Level	Notes
Vessel H	Auxiliary Engine	Caterpillar Inc	C18	1.648	1.411	3.038	1750	CAT071235	01/01/2003	Good - functioning.	565	18.1	1500	EPA Tier 3, IMO II, EU IWW	Currently @ 18596 SMU hours. Last major overhaul carried out @ 17569 SMU.
Vessel H	Auxiliary Engine	Caterpillar Inc	C18	1.648	1.411	3.038	1750	CAT071234	01/01/2003	Good - functioning.	565	18.1	1500	EPA Tier 3, IMO II, EU IWW	Currently @ 24350 SMU hours. Last major overhaul carried out @ 22120 SMU.
Vessel H	Main Engine	MaK	8M 32C	4.371	2.181	7.309	108027	MAK00989898	01/01/2003	Good - functioning.	4000	309	600	EPA Tier 3, IMO II, EU IWW	Currently @89,500 hours. The last major overhaul done @81254 SMU.

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Figure 6-24: Onboard component details on Vessel H.

- Step 3:

Ideally, product specifications data should come from OEMs; however, for this case study, the authors reached out to local dealers of the equipment and entered product information themselves. That is the source of engine technical details, such as main dimensions, weight, power, displacement, and speed, illustrated in the material breakdown presented in Figure 6-25. Other information, such as the serial number, acquired date, and specific notes about each component, comes from Step 2, where the ship owner used the Onboard Components Form to add assets to the vessel. At this point, this PhD thesis does not have permission to publish material breakdowns for this equipment; therefore, they are hidden in Figure 6-25.

Case Study - Onboard Component Material Breakdown on Vessel H

15 December 2023

Vessel Name	Component Type	OEM Name	Model Name	Dry Weight (kg)	Ferrous metals (kg)	Nonferrous metals (kg)	Alloys (kg)	Hazardous Materials (kg)	Others (kg)
Vessel H	Auxiliary Engine	Caterpillar Inc	C18	1750	***	***	***	***	***
Vessel H	Auxiliary Engine	Caterpillar Inc	C18	1750	***	***	***	***	***
Vessel H	Main Engine	MaK	8M 32C	108027	***	***	***	***	***

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Figure 6-25: The onboard component material breakdown details on Vessel H.

- Step 4:

In this step, the financial activity that would be generated from recycling Vessel H in the current industry practice is estimated. Ship recycling stakeholders involved in the database validation step quoted the vessel's value according to today's market.

Considering today's market, the scrap value (V_S) of purchasing the vessel from its owner as a ship recycling facility will be $1,475,000 USD. On top of that, a 15% profit margin is added for ship recycling facilities (Mathew, 2021), and the financial activity generated by the recycling process is estimated at $1,696,250 USD. Furthermore, the recycling stakeholders (experts) provided their estimations on the breakdown of scrap values, as presented in Table 6-2.

Table 6-2: Scrap value of Vessel H with current practices.

Vessel H - Current Practice Case	Symbol	USD	
Scrap value considering today's market	V_s	$	1,475,000
Scrap metals value (hull, outfitting etc.)	V_m	$	1,076,750
Onboard equipment scrap or resale value	V_e	$	398,250
15% Salvaging profit	P_{srf}	$	221,250
Total recycling activity	$V_{t\ current}$	**$**	**1,696,250**

Once the vessel is sold to a recycling facility, it is marked as a recycled vessel in the database. The recycling facility is responsible for updating that information, and when it is updated, corresponding OEMs will be notified, so that they will be able to see their products onboard that particular vessel.

- Step 5:

In Step 5, the potential end-of-life value of Vessel H once advanced circular economy practices are applied is investigated. The database aims to build the connection between ships' end-of-life stages and equipment manufacturing stages. By creating a reverse supply chain, much-needed core component flow for remanufacturing operations will be provided for OEMs. That will result in financial benefits for all stakeholders involved in the process. Therefore, this step dives into the potential financial benefits of marine engine remanufacturing processes for Vessel H.

Firstly, similar to the current practice values, V_s and V_m values are the same. However, V_e is zero, as the onboard equipment will be sent to remanufacturing facilities instead of the direct (as-is) resale or scrapping process.

Previous research on marine engine remanufacturing studies found that remanufactured engines kept 48.3% of their original value with respect to brand-new products (Okumus et al., 2023c). This value was used to estimate the main and auxiliary engine remanufacturing savings, as shown in Table 6-3. Main engine remanufacturing savings ($S_{r_{main}}$) and auxiliary engine remanufacturing savings ($S_{r_{aux}}$) are calculated using Equation 6.1 and Equation 6.2, where *AC* is the acquisition cost and *SF* is the savings factor for the corresponding assets. In this study, both saving factors are taken as 45%.

$$S_{r_{main}} = AC_{new\ main\ engine} * \ SF_{main} \tag{6.1}$$

$$S_{r_{aux}} = AC_{new\ auxiliary\ engine} * \ SF_{aux} \tag{6.2}$$

Table 6-3: Recycling value of Vessel H with advanced circular practices.

Vessel H - Advanced Circular Practices Case	Symbol	USD	
Scrap value considering today's market	V_s	$	1,475,000
Scrap metals value (hull, outfitting etc.)	V_m	$	1,076,750
Onboard equipment scrap or resale value	V_e	$	-
Recycling facility profit	P_{srf}	$	221,250
Savings from advanced CE practices	S_{ce}	$	1,822,500
Main engine remanufacturing	$S_{r\ main}$	$	1,395,000
Gen-set (auxiliary) remanufacturing	$S_{r\ aux}$	$	427,500
Total advanced recycling activity	$V_{t\ circular}$	**$**	**3,120,500**

The estimated total savings from main and auxiliary engines (S_{ce}) is obtained as $1,822,500 USD by using Equation 6.3. This value indicates significant benefits for three main stakeholders in the maritime industry: ship recyclers, OEMs, and ship owners. However, at this stage, it is not possible to assess in what percentages the value will be shared amongst these stakeholders, as the matter is complex and depends on many parameters, and the market has yet to form. At this stage, the author can only say that ship recyclers will not make less profit by becoming suppliers in the reverse supply chain, so in the case study, the recycler is expected to have a share greater than Ve ($398,250 USD).

$$S_{ce} = S_{r_{main}} + S_{r_{aux}} \tag{6.3}$$

On the other hand, when one looks at the industry-level financial activity originated from these advanced recycling processes, the total financial activity generated $V_{t\ circular}$ is estimated at $3,120,500 USD using Equation 6.4.

$$V_{t\ circular} = V_m + P_{srf} + S_{ce} \tag{6.4}$$

- Step 6:

The final step of this case study is the comparison of the value generated with current industry practices (in Step 4) and the potential value generated with advanced circular practices (in Step 5).

The case study reveals that if all onboard engines could be remanufactured, the vessel could generate 83% more financial value, amounting to $3,120,500 USD instead of $1,696,250 USD at the end-of-life stage. The Vessel H case study highlights the significant financial benefits of implementing a functional reverse supply chain and widespread equipment remanufacturing applications in the maritime industry by comparing the value generated through current industry practices with the potential value generated through advanced circular practices. This not only increases the end-of-life financial value of vessels, as demonstrated by the 83% increase in value for Vessel H, but also showcases the broader potential outcomes of adopting advanced circular economy practices in this sector.

6.7.1 Impact Estimation of the Case Study

When one looks at the statistics of the world's commercial fleet, it is seen that between 2014 and 2022, the average annual ship recycling gross tonnage was 18,791,032 GT (UNCTADstat, 2023). This tonnage corresponds to approximately 2400 vessels of case-study size being recycled annually. If the potential impact of the circular economy approach in this research is directly generalised, the value increase would be around $3.40 billion USD annually. This significant value increase highlights the untapped potential of remanufacturing end-of-life engines in the maritime industry. By extending the lifespan of these engines, companies can not only save on costs but can also contribute to a more sustainable and circular economy. With the aforementioned potential annual impact, it is clear that embracing circular economy principles has the potential to revolutionise the industry and create a more environmentally friendly future.

On the other hand, another approach to estimating the impact might be a time-independent, fleet-based analysis. According to the latest data, there are currently 105,395 merchant vessels operating worldwide, with European nations owning 18,703 of these vessels (UNCTAD, 2023). The average size of the total fleet is 14581 GT, which is nearly double the size of our case study Vessel H. As explained earlier, deliberately choosing a smaller vessel than the world average ensures that this research does not overestimate the impact of the circular economy. In this sense, Equation 6.5 is created to estimate the potential impact of this case study.

$$Impact = (S_{ce} * \eta_2 - V_e) * N * \eta_1 \quad (6.5)$$

Where

N is the number of vessels in the impact group,
η_1 is the salvageable vessels ratio among the impact groups,
η_2 is the ratio of the salvageable engine per vessel in the impact group.

Table 4 below shows some important long-term impacts in three scenarios where circular practices reach 1% of the world fleet, the entire European fleet, and one-third of the total fleet. In these estimates, η_1 and η_2 is assumed to be 95% and 67%, respectively. That means 95% of the fleet is assumed to be recycled at some point in their lifespans. Some vessels can be lost, sunk or unsalvageable due to other reasons. This study also assumes that, from every three engines that make it to a ship recycling yard, only two of them are remanufacturable. As shown in Table 6-4 below, the European fleet single-handedly has a $14.5 billion USD end-of-life value increase potential, while one-third of the world fleet nearly doubles this amount.

Table 6-4: Long term impact estimates.

Impact Group	N	Impact (millions USD)
1% of the world fleet	1054	$ 818 M
Total European fleet	18703	$ 14,512 M
1/3 of the world fleet	34780	$ 26,986 M

6.8 Chapter Summary

This chapter addressed a significant gap in the circularity journey of the maritime industry: the absence of asset tracking systems and digital infrastructure. To bridge this gap, the MAT concept was introduced and supported by the development of a maritime-specific database. The case study involving an 8525 GT vessel illustrated the practical advantages of this digital tool, revealing that the vessel could generate 83% more value at end-of-life if onboard engines were remanufactured within a circular ecosystem. The findings highlight the transformative potential of digital infrastructure, with the impact estimation indicating a financial benefit of 14.5 billion USD for the European fleet and 27 billion USD for one-third of the world fleet. These results underscore the importance of digital tools in enabling circular practices, improving resource efficiency, and enhancing financial outcomes. This chapter demonstrates that digital infrastructure is not merely a supporting tool but a critical enabler of advanced circular practices in the maritime industry.

7 Developing Novel Circularity Metrics for the Maritime Industry

7.1 Chapter Overview

This chapter focuses on circularity performance monitoring and industrywide alignment to achieve a higher circularity level. It represents the final component of the maritime circularity framework in Phase II. Chapter 7 provides an in-depth analysis of current CE metrics in the literature and based on this examination, introduces specific metrics tailored to maritime stakeholders. These metrics were subsequently linked to five key industry aspects: financial considerations, supply chain operations, raw material usage, waste and emissions management, and social dimensions. Finally, a case study demonstrates the practical application of the developed metrics in the real world, specifically highlighting the step-by-step implementation of these metrics in ship repair yards. This chapter has been partly published in the Ocean Engineering journal (2024) volume 312, part 2 as follows:

Okumus, D.; Andrews, E.; Gunbeyaz, S.A. Developing circularity metrics for the maritime industry: A stakeholder focused study. *Ocean Engineering* **2024**, *312*, 119168. https://doi.org/10.1016/j.oceaneng.2024.119158

7.2 Background

As the core of the CE concept consists of economic development and the reduced environmental impact of economic activities (Stahel, 2010), CE approaches are expanding in popularity substantially while addressing raw material concerns, encouraging innovation, and boosting opportunities for a skilled workforce (Kristoffersen et al., 2021). The evolving regulatory landscape is also one of the motivations for the industry to introduce circularity practices. EU's Corporate Sustainability Reporting Directive, introduced by the European Parliament in 2022, requires companies to disclose their impact of activities on the environment and society. This regulatory push encourages companies to integrate circular practices into their operations. In addition to the regulatory pressures, recent standardisation efforts also played a significant role in promoting circularity, such as the new ISO family of standards, which provides a framework for implementing CE principles (ISO 59000 family (ISO, 2024b)) and offers specific indicators for measuring circularity (ISO 59020 (ISO, 2024a)).

However, transitioning to CE from a conventional linear economy, industry, or business dynamics can be extremely challenging. Usually, a real system's design intent and actual performance can be quite different. Though it is possible to create elegantly circular systems, the users and stakeholders in the actual product or service will determine how circular the system performs (Ellen MacArthur Foundation & Granta Design, 2019). Figure 7-1 displays how the execution of a circular transition could differ from the envisioned theoretical design, and it is not a simple linear way of achieving the intended benefits.

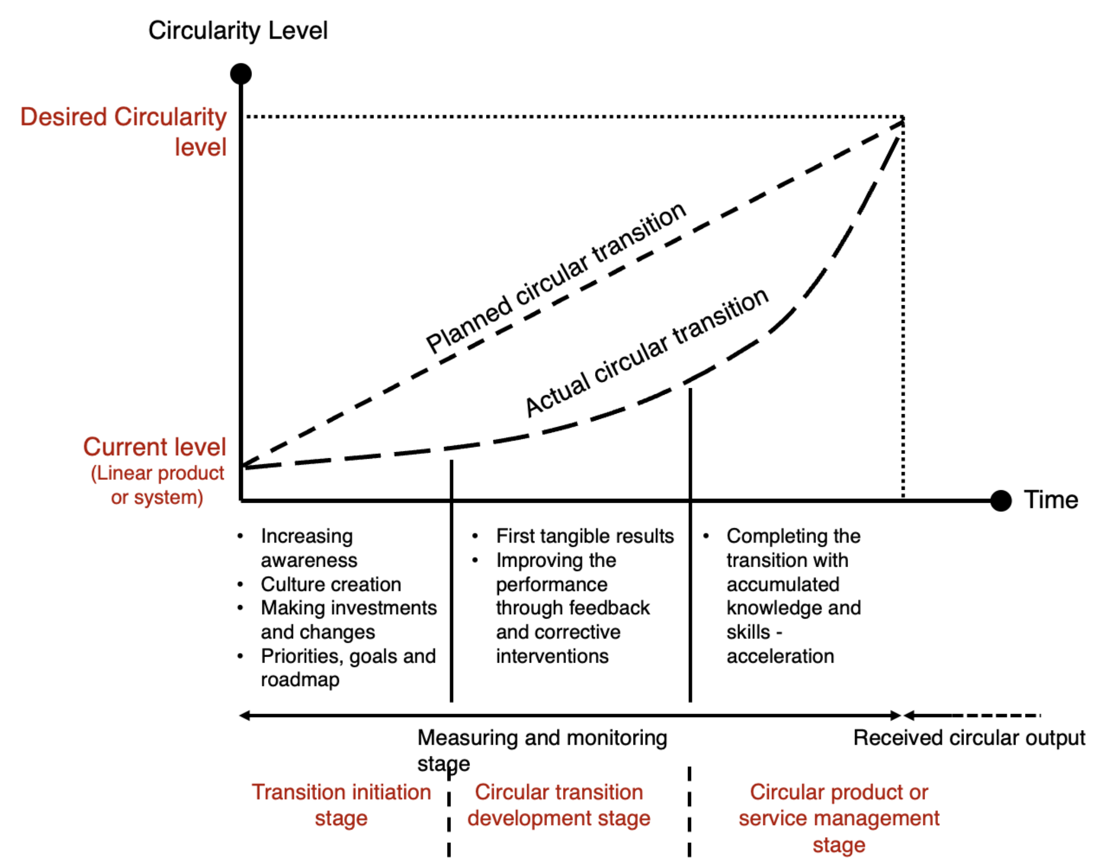


Figure 7-1: Differences between the designed and actual circular economy transition, adapted from *(Ellen MacArthur Foundation & Granta Design, 2019)*.

The unique structure of the CE concept also requires an advanced closed-loop supply chain, or, in other words, a reverse supply chain. A mismatch between demand and supply in the reverse chain contributes to the quality and value-related uncertainties that create the major challenges of a circular system (Lopes de Sousa Jabbour et al., 2018). The lack of information throughout the industrial lifespan is one of the fundamental causes of these potential issues (Wilts & Berg, 2018). While modern digital infrastructures, information systems, and technological solutions can significantly improve the reverse supply chain, monitoring the overall company's circularity progress and performance is necessary.

In order to monitor the outcomes of CE adoption and to assist practitioners, policymakers, and decision-makers, new industry-specific tools are needed. Academics, businesspeople, and politicians from all around the world concur that to manage this transformation at systematic levels, CE-related indicators, or key performance indicators (KPIs), are essential (Saidani et al., 2019). The lack of KPIs is highlighted as a significant challenge for circularity according to a recent study by Kristoffersen et al. (2021), which carried out a thematic research to identify gaps. They identified a lack of industry- or business-specific CE KPIs to benchmark performance, causing a lack of top management buy-in. Circularity metrics, tailored or applicable to any selected industry, are urgently needed to assess and measure the progress towards the circular economy (Ellen MacArthur Foundation, 2022). These metrics will provide valuable insights into the circularity of products, processes, and systems, enabling companies to track their performance, identify improvement opportunities, and drive continuous innovation towards a more sustainable future (Rincón-Moreno et al., 2021). By utilising these indicators and a data-driven approach, companies can make informed decisions on resource efficiency, waste reduction, and overall environmental impact and sustainability. Although there are generic KPIs developed for circularity, these metrics might not apply to all industries and need to be tailored.

The transition into CE is also essential for the maritime industry, as it is the backbone of the global economy since it moves over 80% of world trade by volume, and the world trade volume is predicted to triple by 2050 (UNCTAD, 2022b). On the other hand, the maritime industry still has much to improve to draw a circular industry portrait. In fact, the industry lags behind other modes of transportation in terms of circular economy, but this also means that there is significant potential to be realised (Okumus et al., 2023b). Even though significant steel recycling practices exist, there are no structured advanced circular economy practices such as repurposing, remanufacturing, or reusing in the life-cycle of a ship (Okumus et al., 2023c). Moreover, considering the maritime industry’s pledge to reduce its operational GHG emissions (Milios et al., 2019)—initially by 50% by 2050 (IMO, 2018a), and then raising the bar to at least 70% in 2040 and eventually net zero by or around 2050 (IMO, 2023)—the potential environmental impact of refitting/rebuilding the fleet will be tremendous. Therefore, applying circularity principles to the maritime industry is critical for its long-term sustainability (Wahab et al., 2018) and helping decarbonisation efforts in the sector (Okumus et al., 2023c).

There are numerous CE-focused studies in the literature, some of which have come up with circularity indicators to track the circularity of a business or stakeholder. It reached the point where studies went as far as to create taxonomies to classify these metrics efficiently. On the other hand, until now, there has been no way to track progress and ensure that the maritime circularity transition is measured (Okumus et al., 2023b). Only ports have been addressed among all maritime stakeholders regarding CE indicators (Faut et al., 2023). There is a clear gap within the current literature to present indicators for the maritime industry and wider stakeholders (ship designers, original equipment manufacturers, shipbuilding yards, classification societies, owners/operators, ship repair yards, cargo owners, recycling facilities, and authorities). The maritime industry urgently needs these metrics, enabling stakeholders to benchmark their current CE performance and develop a circularity roadmap to include advanced circularity practices such as reuse, remanufacture, reduce, redesign, and recover. The maritime industry is approaching the CE concept with a focus on recycling. However, according to the CE principles and waste hierarchy, recycling is the least desired end-of-life option for end-of-life equipment and materials (Gilbert et al., 2017). Therefore, the metrics will also demonstrate the industry's best practices through benchmarking and provide pathways for further sustainability.

Therefore, this novel PhD research aims to explore and develop a set of circularity metrics for maritime stakeholders, such as ship owners, shipyards, OEMs, recycling facilities, etc. By covering these major stakeholders in the maritime industry, a more comprehensive understanding and initiation of circularity within the sector can be achieved. The overall aim has been achieved through a series of objectives. Initially, a set of stakeholder engagement activities was conducted within this study to identify the current circularity practices, gaps, and industry needs. This was followed by a thorough review of existing CE indicators documented in the literature. Subsequently, the relevance of these indicators to the maritime industry was examined, with an initial filtering process to identify the most relevant ones. Building upon this, these indicators were consolidated and refined, shaping them into metrics tailored specifically for the maritime sector, considering significant stakeholders and all life cycle stages. Workshops and interviews with maritime stakeholders were organised to ensure these metrics' practicality, effectiveness, and validity. Finally, a representative case study was conducted to demonstrate the real-world application of these metrics.

This research will contribute to filling the aforementioned gap in circularity metrics for maritime stakeholders, leading to a more holistic approach towards sustainable practices in the industry. Ultimately, the development of these metrics can drive greater adoption of CE principles throughout the maritime sector by providing a method of measuring progress, and it will provide valuable insights for policymakers, businesses, and researchers looking to promote circular practices in maritime operations.

Therefore, this research is a big step towards maritime circularity, developing a set of circularity indicators for the maritime industry and a novel contribution to the literature and industry knowledge. This research is the first time that indicators for CE have been reviewed and applied directly to the wider maritime industry. A comprehensive, desk-based review of over 400 indicators from the literature was conducted. These indicators were then analysed for their applicability to the maritime sector through a stakeholder workshop, and a unique set of metrics tailored specifically for use in the maritime industry was produced. This thorough approach ensures completeness to the set of metrics and solidifies the metrics as fit-for-purpose for a complex and challenging industry. Moreover, this research dived into the maritime industry's stakeholder groups and stakeholder-specific dynamics and requirements. By understanding stakeholders' specific needs and dynamics within the maritime industry, this study aims to develop tailored CE metrics that can effectively measure the transition to circularity.

This chapter is structured into six sections. Section 7.3 outlines the chapter methodology, while Section 7.4 reviews of existing CE metrics and indicators. Section 7.5 presents circularity metrics developed for maritime stakeholders and associates the metrics with major industry aspects. Section 7.6 illustrates the case study, followed by the chapter summary in Section 7.7.

7.3 Chapter Methodology

This study was conducted in four main steps, as shown in Figure 7-2. Firstly, initial stakeholder engagement was undertaken through three workshops centred around maritime CE to understand the maritime industry's needs. Subsequently, a systematic literature review gathered papers detailing CE indicators from sector-specific papers and those about more general sustainability measurement. Those indicators were divided into the three main categories of sustainability: environmental, social and economic. To identify the suitability of these indicators, the researchers assessed each one using the filtering criteria:

- Does this indicator show circularity performance?
- To which stakeholders can this indicator be applied?
- What stage in the lifecycle is it applicable to?

The third step of this research was to develop CE metrics (CMs) specifically for the maritime sector. An industry case study was then carried out to ensure the indicators' applicability and appropriateness to the maritime industry. Finally, stakeholders were re-approached to provide input into the development of the industry and stakeholder-specific CMs. This collaborative process resulted in a final set of CMs, which were then tested in a case study, further validating the metrics.

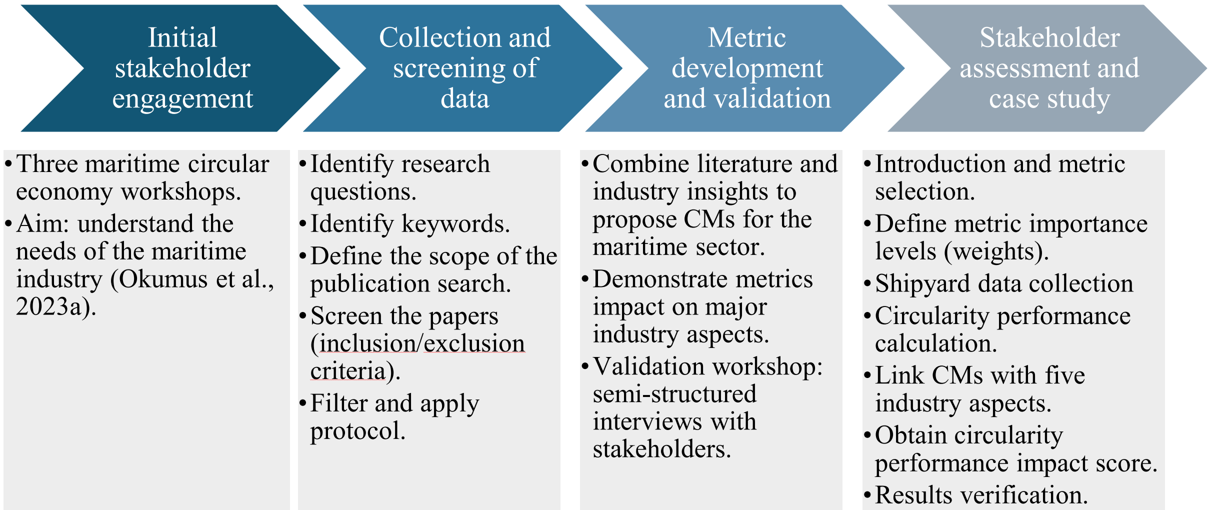


Figure 7-2: Chapter methodology.

7.3.1 Initial Stakeholder Engagement

Three circular economy workshops were organised to understand the research need in maritime circularity (Okumus et al., 2023a). Two workshops were carried out in person, and one was online, and all took place between December 2022 and February 2023, and were attended by 73 maritime professionals from various backgrounds, including shipyards, ports, ship operators, classification societies, academia and policymakers. The workshops involved four steps: defining maritime circularity, a gap analysis, a strengths, weaknesses, opportunities and strengths (SWOT) analysis, and a discussion on generating future strategies. Two key findings from these workshops were the need to measure and monitor the circularity performance and a keen interest in case studies showing circular economy principles. This initial stakeholder engagement, therefore, resulted in the understanding of this research in CMs for the maritime industry, with an accompanying case study.

7.3.2 Collection and Screening of Data

To commence the literature review part of this study, the following research questions were defined:

- What indicators and metrics are there for measuring CE performance?
- How relevant are they to the maritime industry?
- What is needed by the industry to understand CE performance better?

A systematic literature review was conducted to answer these questions. The research protocol was developed by defining the inclusion and exclusion criteria (Table 7-1). The inclusion criteria included papers limited to the last ten years to capture the most recent research, and therefore, papers published between 2014 and 2023 were considered. Only journal articles and reviews written in English were considered, and the research subject areas were limited to engineering, science and technology, environmental sciences, business, and management.

Five keywords appropriate for answering the research questions were selected as follows: "circular economy indicator", "circularity metrics", "circular economy metric", "circular KPI", and "circularity indicator" for a systematic literature review by using the Web of Science and Science Direct databases. These searches returned 473 publications from Science Direct and 104 from Web of Science. This initial search provided ample papers for this study, and ending the search at these databases was deemed satisfactory.

The filtering process (Table 7-2) excluded duplicates, full-text-missing publications, and papers focusing on irrelevant industries or specialised sectors (e.g., petroleum, chemical, textile, agri-food). Then, the papers' abstracts were read to check their alignment with the scope of this study. Subsequently, the number has been reduced to 57 publications, and these remaining papers were fully read to capture their key findings and contributions to the field. This rigorous screening process ensured that only the most relevant and impactful research was included in the remaining analysis.

Table 7-1: Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Papers published between 2014 and 2023. Papers written in English and published in Science Direct (473) and Web of Science (104).	Duplicates, full-text-missing publications, and papers focusing on irrelevant industries or specialised sectors (e.g., petroleum, chemical, textile, agri-food).

Table 7-2: Publication filtering steps.

First filter	Second filter	Third filter
Duplicates, full-text-missing publications, and papers focusing on irrelevant industries or specialised sectors (e.g., petroleum, chemical, textile, agri-food)	Scan of abstract. Check that paper meets inclusion and exclusion criteria.	Read of full paper (57).

7.3.3 Metric Development and Validation

The CMs in the selected publications were then listed to compile an initial list of 495 metrics. The indicators were screened for duplicates, which were removed from the database. They were then categorised into economic, environmental, and social subgroups. Following this categorisation, the CMs were further screened using two-step filtering: whether they were specific to the CE concept and the second was the connection of metrics with the maritime industry. Subsequently, the metrics that were found to be related to maritime circularity were reduced to 62. Following this compilation and filtering of the indicators, a final assessment was run by asking the following questions:

- Does this indicator show circularity performance for maritime?
- To which maritime stakeholders can this indicator be applied?
- What stage in the ships' lifecycle is it applicable to?

Following this filtering of compatible CE indicators from the literature, dedicated circularity metrics for maritime were proposed within this chapter by adopting these selected indicators. In the final step, a stakeholder-focused assessment was carried out to validate the developed CMs for the maritime industry. This involved engaging with various experts from the maritime industry to gather input on the metrics' relevance and feasibility. This collaborative process established a final set of circularity metrics specific to the maritime sector for further evaluation and implementation. Following the workshop and semi-structured interviews, suggested metrics were validated and finalised. Appendix E presents the experience levels and backgrounds of the participants to metric validation workshops. Moreover, during the workshops, the impact of monitoring circularity on major industry aspects, namely financial, supply chain, material requirements, waste and emissions, and social, was revealed.

7.3.4 Verification through a Case Study in Ship Repair

In the final step of this research, a case study for one of the critical stakeholders, repair shipyards, was selected as a pilot to assess the effectiveness and practicality of the circularity metrics in real-world applications. Three private repair shipyards in Turkey participated and provided invaluable contributions to verifying the circularity metrics. The case study steps involved the following steps: the initial phase involves outlining the objectives and introducing the metrics to shipyard participants. Subsequently, weights are assigned to metrics based on their significance based on semi-structured discussions. As Appendix D outlines, data collection is conducted to gather required information from the shipyard operations. Utilising this data, the circularity score is calculated through the metrics. These metrics are then linked with five key industry aspects through the Analytical Hierarchy Process (AHP) to provide a comprehensive assessment. Then, the circularity performance benchmarking was finalised for each shipyard and compared performances. Finally, results are further discussed with stakeholders to ensure accuracy and reliability, thereby validating the effectiveness of the evaluation process. The detailed case study steps are explained in Section 7.6.

7.4 Review of Existing CE Metrics and Indicators

While the existing literature offers various indicators of CE, many of these metrics are not universally applicable across all industries due to their context-specific design. For example, the circular economy index proposed by, Di Maio and Rem (2015) measures the difference between the material value entering the recycling facility and the material value produced by the recycler. Through a simplified car recycling case, authors demonstrated a better ability to handle cases where the material was produced in alternative ways than traditional lifecycle analysis. However, its application may be limited in complex and diverse contexts. Similarly, the "Circular economy performance indicator" (CPI) by Huysman et al. (2017) focuses on the ratio of the actual environmental benefit (as a result of the waste treatment option used) to the ideal environmental benefit as a function of quality. In other words, CPI considers downgrading end-of-life products during recycling processes. As a case study, the researchers demonstrated how to manage various end-of-life product (plastic waste) streams with different quality levels. Although the approach is useful for managing end-of-life plastic waste, its effectiveness for maritime with varied product life cycles and quality requirements is unproven. Linder et al. (2017) emphasised the importance of achieving a unified circularity score by the end of the assessment and introduced another metric concerned with product-level circularity, which measures the ratio of the economic value of recirculated parts over the economic value of all parts forming the product. In this study, a consistent aggregation approach is adopted to calculate the circularity metric for a product. The study used plastic toys and more advanced starter engine remanufacturing as case studies. On the other hand, metrics do not address the various life cycles and diverse maritime stakeholders.

Ellen MacArthur Foundation and Granta Design (2015) increased the CE concept's traction by presenting a business rationale, outlining circular value creation and opportunities, and identifying building blocks for transitioning to a CE. Then, they developed an indicator for businesses to assess their circularity performance and identify areas for improvement. The material circularity indicator (MCI) by the Ellen MacArthur Foundation first calculates the linear flow index (LFI) to determine the proportion of materials flowing linearly over the total material flow (both linear and circular flows), then forms a function using LFI as a variable with a factor that is flexible for different products to estimate MCI (Ellen MacArthur Foundation & Granta Design, 2019). On the other hand, the metrics introduced are high-level only and the overall approach relies on factors that vary with product types, which may pose challenges for comparability across stakeholders.

The concept of recyclability benefit rate, by Huysman et al. (2015), represents the ratio of the possible environmental savings from recycling a product to the environmental costs associated with its virgin production and disposal. Value-based resource efficiency (VRE) approach of Di Maio et al. (2017) comprises monetary values of gross output, energy, material, and service costs to produce the output. The authors compared the traditional indicators and VRE in various sectors and the study emphasises that circularity metrics have important implications for resource efficiency and deciding focus areas for policymaking. While both Huysman and Di Maio's approaches were innovative, these metrics do not capture the full picture of CE in sectors that have tailored (or custom-made), large-scale complex products with multi-stage manufacturing processes such as maritime. Figge et al. (2018) proposed an approach that combines circularity measurement with a focus on longevity, demonstrated through gold minerals in mobile phones. Their metric considers when a resource is first used, refurbished and recycled, separately. On the other hand, open-loop recycling, where resources are reused in different products, is out of scope.

A recent study by Ibáñez-Forés et al. (2022) analysed 255 indicators from the territorial CE programmes of the EU, Spain, Germany, France, the Netherlands, China, and Japan. The authors proposed a set of indicators and demonstrated these in forestry and paper products sectors (34 indicators grouped into 10 categories) to enable measuring companies' circularity levels and cover various product life stages and business aspects such as design, suppliers, inputs, production, environmental impact, research and development activities, communication, etc. On the other hand, some metrics work more like a checklist showing whether certain milestones are achieved rather than a mathematical expression (e.g., whether the organisation integrates reverse logistics or operational steps, such as providing preventive maintenance or after-sales services, etc), failing to address the unique nature (custom-made products and operational processes) of the maritime industry.

Bracquené et al. (2020) have developed the product circularity indicator (PCI) to improve MCI by allowing different restorative flows to re-enter the production chain at appropriate stages. By doing so, PCI differentiates between recycled and reused materials during the restorative production cycle. PCI also provided a case study for washing machine production as well. Most of these metrics and indicators are aimed at producers or OEMs, which are companies that manufacture parts, components, or entire products. Publications or case studies for OEMS mainly focus on mass manufacturing products, such as automobiles, white goods, small home appliances, electronics, etc. However, the nature of the maritime industry and shipbuilding processes at shipyards differ from those at a traditional manufacturing plant since each product is unique and tailor-made for the user's needs, or shipowners’ in this case. The maritime industry and shipbuilding processes involve unique challenges and complexities not typically encountered in traditional manufacturing environments. These complexities include the size, type, operational features, cargo characteristics and scale of the vessels being built, the need for specialised equipment and materials, and the intricate coordination required among various stakeholders. A systematic and applicable framework is essential for effectively assessing and enhancing circular practices. That begins with revealing current levels and regularly monitoring future progress. Therefore, developing specific circularity metrics tailored to the maritime industry is crucial for effectively measuring performance and identifying areas for improvement.

Additionally, showcasing how metrics can be used in practical situations through case studies is advantageous for helping industry stakeholders grasp the concept and engage in the shift towards a circular economy. Enhancing the case studies by incorporating stakeholders' internal processes could improve their effectiveness. For instance, case studies simulating shipbuilding processes might not only reveal their impact on circularity metrics but also provide valuable insights into optimising the efficiency of the shipyard.

Apart from the metrics mentioned above, a wide body of literature also focuses on simpler and more fundamental indicators of CE. These indicators usually provide a general viewpoint by covering most standard business functions, regardless of industry-specific details. A recent study by Calzolari et al. (2022), which dived into the literature and analysed 203 papers from 99 different sources. Publications showed a sustained growth in the number of papers published starting in 2015. The collected metrics were categorised into economic, environmental, and social dimensions, from most to least commonly represented. The three dimensions are divided into 19 categories, and their occurrences are analysed, showing the importance of financial, supply chain, resource usage, waste generation, emissions, and social perspectives. De Pascale et al. (2021) carried out a systematic review of CE indicators for micro, meso, and macro levels and specified 61 different metrics. Reviewed indicators were assessed and grouped according to their potential ability to capture the three dimensions of sustainable development and the 3R principles of CE. A lack of structured and standardised methodologies to evaluate CE is underlined.

Similarly, de Oliveira et al. (2021)'s review on CE indicators revealed that most publications addressing nano- and micro-level circularity, including grey literature contents, are traced to European countries. A total of 58 nano- and micro level indicators were examined in detail. Their connection with sustainability dimensions and product lifecycle stages is investigated. More recently, Jerome et al. (2022) conducted a study to map existing indicators to measure CE at the product level circularity indicators and analysed the indicators through seven case studies. Circularity indicators and LCA results were compared, and it was concluded that the indicators cannot easily replace LCA. Another key finding is that, currently, no multi-focus indicator addresses the entire CE concept. Kristensen and Mosgaard (2020) reviewed micro-level CE indicators and their alignment with sustainability dimensions and found that the majority of the indicators focused on recycling, EOL management, or remanufacturing, while fewer indicators considered disassembly, life extension, waste management, resource efficiency, and reuse. This review identified nine CE categories to classify the most used CE keywords and principles and analysed the relationship between existing indicators and nine categories. There is no commonly accepted way of measuring CE in general at the micro level, and there are indicators lacking, particularly for monitoring the progress of high-circularity R-strategies. Franco et al. (2021) have suggested a framework aiming to monitor CE performance at the micro-level by integrating multicriteria decision-making methods. 58 initial CE indicators were associated with the R-strategies (ten RE-terms) were collected. Authors utilised expert participation and multi criteria decision making methods to reveal the most relevant CE metrics for each R-strategies such as reduce, recover, remanufacture, etc., then defined composite CE indicators were associated with R strategies.

There are also publicly accessible and reputable reports, such as ETSI TR 103476 (ETSI, 2018), which introduces the CE concept and suggests basic circular economy metrics for different product lifecycles. HOUSEFUL project deliverables point out reference KPIs and methodologies for circular practices (HOUSEFUL, 2019). Also, the Ellen MacArthur Foundation's Circulytics initiative provides a comprehensive framework for measuring circularity across various sectors and industries (Ellen MacArthur Foundation, 2022). Additionally, widely known organisations from the transportation and power generation industries—for instance, Caterpillar—have developed their own circular economy goals and indicators to help businesses track and evaluate their progress towards circularity (Caterpillar, 2023), as their restorative operations have seen notable improvement and expansion over the last four decades, currently employing a workforce of over 3600 individuals around the globe (Ellen MacArthur Foundation, 2021). Groupe Renault, on the other hand, has also invested heavily and opened the first European facility dedicated to the CE of mobility, called Re-Factory, where reuse, repair, remanufacture, and recycling of parts are all integrated, as well as reconditioning and retrofitting of used vehicles (Groupe Renault, 2022). These resources offer valuable guidance and tools for measuring and monitoring circular performance at different assessment levels.

Regarding the sustainability indicators, Mesa et al. (2018) have devised a set specific to product families based on CE principles. The authors proposed six indicators, which cover material flows, potential reuse portion, recycling degree, and functionality performances of product designs. Proposed metrics were validated on prosthetics and study emphasises the crucial importance of the design and underlines the broader scope of circularity considerations within sustainability assessments. Additionally, Kravchenko et al. (2019) concentrated on the ex-ante sustainability screening of circular economy activities in manufacturing companies, emphasising the consolidation of key sustainability-related performance indicators. They underlined the importance of social performance criteria, particularly in determining product affordability. This highlights the importance of adding social considerations to evaluating CE efforts.

Franklin-Johnson et al. (2016) have introduced a unique longevity indicator focusing on resource duration, providing a nuanced perspective on circular performance assessment. The indicator takes remanufacturing or refurbishing lifespan contributions and contributions from recycling operations into account, along with the initial product lifespan. However, their model calculates longevity for a certain case, failing to accommodate different variations of recycle, reuse and remanufacture mix. Longevity plays an important role in product design and sustainable value chains. Complementing this, Hapuwatte and Jawahir (2021) have presented a metrics-based product evaluation framework for closed-loop sustainable product design, emphasising the importance of integrating circularity metrics in the early stages of product development.

However, Sassanelli et al. (2019) systematic literature has highlighted a notable gap in current industry practices. The measurement and assessment of circularity performances are not yet common in companies, indicating a need for wider adoption of circular economy performance assessment methods within organisations. Recognising this gap, Valls-Val et al. (2022) reviewed tools for organisations to measure their circularity levels. Their study highlighted a specific void: while indicators had been established at the territorial level in the EU context, organisation-specific indicators were lacking. One of the recent efforts is the ISO's 59000 family of standards, which provides a structured framework for implementing CE principles; notably, 59020 offers a set of indicators measuring circularity.

The comprehensive review revealed that the maritime industry has not been previously included in metric investigations. Existing metrics in the literature are unsuitable for the maritime industry due to its unique characteristics. This highlights the need for tailored metrics that address the sector's future circularity, sustainability, and decarbonisation goals. This gap motivates the present research, which aims to define circularity metrics specific to the maritime industry and its key stakeholder groups, and to evaluate their circular economy performance. By developing these industry-specific metrics, this research will enable maritime organisations to assess their circularity levels and identify areas for improvement accurately. This will ultimately contribute to the overall sustainability and efficiency of the maritime industry, aligning it with the principles of a circular economy.

7.5 Results and Analysis

7.5.1 Stakeholder-Focused Circularity Assessment

In this section, the author proposes tailored circularity metrics for each maritime stakeholder based on the literature review and considering the industry dynamics. These metrics are not exhaustive or definitive and can be adapted depending on the context and scope of the circularity assessment. Each stakeholder in the maritime industry has distinct roles, responsibilities, impacts, and influences on the industry's circularity. Therefore, it is important to identify and measure each stakeholder's circularity performance and impact using appropriate and relevant circularity metrics. Considering the impact, this study focuses on stakeholders: ship designers, original equipment manufacturers, shipbuilding yards, classification societies, owners/operators, ship repair yards, cargo owners, recycling facilities, and authorities. Seafarers and ports are not included in the scope of this study.

Since there is neither an authority forcing such an assessment nor a regulation or standard to guide the stakeholders, the flexibility in choosing and adapting circularity metrics allows for a more customised and relevant evaluation of sustainability efforts within the maritime industry. This approach encourages greater engagement and participation in CE initiatives by allowing stakeholders to select metrics that align with their specific goals and priorities. The proposed CMs can also serve as a practical reference or a starting point for regulatory bodies and authorities. This bottom-up approach can lead to more innovative and effective sustainability strategies tailored to each stakeholder group's distinct circumstances.

The author has proposed maritime circularity metrics by combining the CE frameworks discussed in the literature review section with their prior experience of the outcomes of three maritime circular economy workshops conducted (Okumus et al., 2023a). In other words, this approach is based on current CE literature and the involvement of maritime industry professionals from all stakeholder groups included in this study. Such an approach ensured that the proposed metrics were not only theoretically sound but also practically applicable to the maritime industry's unique context (Okumus et al., 2024a). For instance, the metrics addressing the reverse supply chain were directly influenced by recent publications in circular supply chains (Bracquené et al., 2020), closed-loop material flows (Hu et al., 2022), and circular material management tools available (Valls-Val et al., 2022) in the literature. Figure 7-3 illustrates an overview of all the CMs made for this study. It connects the metric themes to important literature references used in this research and shows the stakeholder groups that are related to them. Table C-7 in Appendix C provides a list of the metric definitions.

Moreover, depending on the availability of the participants, smaller workshops or semi-structured stakeholder interviews have been carried out for each stakeholder group to validate and refine the proposed metrics and increase their relevance and effectiveness in addressing the specific needs and challenges of the maritime industry. The participants were selected based on their knowledge, experience, and active involvement in the maritime industry (as presented in Appendix E), ensuring their assessments would strengthen the metrics' practicality and potential adoption by industry professionals. Moreover, these discussions served to identify the connection between CMs and the five major industry aspects specified in Section 7.5.2.

Circularity Metric Themes	Related References	Maritime stakeholder groups: Ship designers (SD)	OEMs	Building Shipyards (BS)	Classification Societies (CS)	Owners/ Operators (OO)	Repairing Shipyards (RS)	Cargo Owners (CO)	Recycling Facilities (RF)	Authorities (Local/int, flag, port state etc.) (AUT)
Durability, longevity	Franklin-Johnson et al. (2016), Figge et al. (2019), ETSI (2018),	SD-CM 1	OEM-CM 2	BS-CM 4		OO-CM 1				
Modularity	Hapuwatte et al. (2022), ETSI (2018), Mesa et al. (2018)	SD-CM 2	OEM-CM 3	BS-CM 1						
RRR content ratio	Huysman et al. (2015), Hapuwatte et al. (2022), Mesa et al. (2018), Bracquené et al. (2020), Linder et al. (2017)	SD-CM 3	OEM-CM 1	BS-CM 2		OO-CM 2; OO-CM 3	RS-CM 2; RS-CM 3	CO-CM 2		
Lead time	Calzolari et al. (2022), Hu et al. (2022)		OEM-CM 4				RS-CM 1		RF-CM 7; RF-CM 8	
Financial share	Ibáñez-Forés et al. (2022), Di Maio and Rem (2015), Hapuwatte et al. (2022)	SD-CM 4	OEM-CM 10	BS-CM 3			RS-CM 6		RF-CM 1; RF-CM 2	

Customer involvement	Ellen Macarthur Foundation (2022), Ibáñez-Forés et al. (2023)	SD-CM 5	OEM-CM 8	BS-CM 5			RS-CM 7	CO-CM 1		
Emission reduction	Hapuwatte and Jawahir (2021), Kristensen and Mosgaard (2020)		OEM-CM 6	BS-CM 7			RS-CM 9		RF-CM 3	
Reduced waste	de Oliveira et al. (2021), Jerome et al. (2022), Franco et al. (2021)		OEM-CM 7			OO-CM 6; OO-CM 8	RS-CM 4	CO-CM 1	RF-CM 4; RF-CM 5; RF-CM 6	
Hazardous waste	Hapuwatte et al. (2022), Franco et al. (2021)		OEM-CM 9	BS-CM 6		OO-CM 7; OO-CM 9	RS-CM 8			
Quality of CE products	Huysman et al. (2017), De Pascale et al. (2021)		OEM-CM 5		CS-CM 1; CS-CM 2; CS-CM 3; CS-CM 4					AUT-CM 1; AUT-CM 2
Reverse supply chain	Bracquené et al. (2020), Hu et al. (2022), Valls-Val et al. (2022)				CS-CM 5	OO-CM 4; OO-CM 5	RS-CM 4; RS-CM 5		RF-CM 7; RF-CM 8	AUT-CM 3
Rules, standards or regulations	Di Maio and Rem (2015), Ibáñez-Forés et al. (2022)				CS-CM 1; CS-CM 2					AUT-CM 1; AUT-CM 2; AUT-CM 4

Figure 7-3: An overview of developed CMs within this study.

7.5.1.1 Ship designers (SD)

Ship designers are responsible for creating the conceptual and detailed design of vessels, considering their customers' functional, technical, economic, and environmental requirements, regulations, and standards. For a service or product, CE mentality starts at the very beginning of its lifespan, the design phase. Ship designers can adopt CE principles by designing durable, modular, adaptable, recyclable ships that use recycled or renewable materials. The circularity metrics developed for the designer stakeholders are as follows.

SD-CM 1. Durability indicator, longevity of the design: This metric measures the expected lifespan of the ship design based on the quality, reliability, and maintainability of the materials and components used. SD-CM 1 can be expressed as the ratio of the average design life of ships to the average lifespan of the same-class vessels in the world, as shown in Equation 7.1.

$$[SD - CM\ 1] = \frac{Average\ design\ life\ of\ ships\ designed_{annual}}{Average\ lifespan\ of\ same\ class\ vessels\ _{annual}} \quad \text{(Eq. 7.1)}$$

SD-CM 2. Modularity of Design Indicator: Removability, modularity, upgradability, and recoverability concepts from the literature are combined together to form this metric, which measures the degree to which the design allows for easy removal, replacement, upgrade, or recovery of parts and components without compromising the structural integrity or performance of the ship. The metric does not focus on the entire ship; it can cover particular equipment and systems onboard depending on the vessel type. For instance, engine room modularity or propulsion system. This metric can be expressed as a modularity score based on a predefined scale for the engine room example, as illustrated in Table C-1 in Appendix C.

SD-CM 3. The recycled-reused material proportion by mass: This metric measures the amount of recycled or reused materials used in the designed vessel, comparing their ratio to the total materials needed to build the vessel. A higher proportion of recycled or reused materials means less demand for virgin raw materials and less environmental impact for the particular design. The metric can be formulated as a percentage of recycled or reused materials by mass (W in tonnes), as shown in Equation 7.2.

$$[SD - CM\ 3] = \frac{W_{recycled\ or\ reused\ materials}}{W_{\ total\ materials}} \quad \text{(Eq. 7.2)}$$

SD-CM 4. Cost distribution of new, remanufactured, and reused onboard components: SD-CM 4 is concerned with using recovered parts and components in designed vessels. This metric can be expressed as a percentage of the cost of remanufactured or reused parts and components over the total cost of onboard parts and components (C is cost in US dollars). An increase in this metric means more circular parts and components are included in ship design as depicted in Equation 7.3.

$$[SD - CM\ 4] = \frac{C_{remanufactured,refurbished\ or\ reused\ components}}{C_{new,remanufactured,refurbished\ or\ reused\ components}} \quad \text{(Eq. 7.3)}$$

SD-CM 5. Ratio of customers offered designs with circular products onboard: SD-CM 5 indicates the market demand and acceptance of ship designs that incorporate circular products such as remanufactured or reused parts or components, or renewable engineering solutions. The metric can be defined as a percentage of the number of customers who ordered designs with circular products on board, compared to the total number of customers served each year, as shown in Equation 7.4, where *N* stand for the number of customers.

$$[SD - CM\ 5] = \frac{N_{customers\ provided\ circular\ designs}}{N_{total\ customers\ served}} \quad \text{(Eq. 7.4)}$$

7.5.1.2 Original equipment manufacturers (OEMs)

OEMs are original equipment manufacturers that produce and supply parts or components for ships, such as main and auxiliary engines, pumps, hydraulics, navigation electronics, etc. OEMs can adopt circular economy principles by producing parts or components that are durable, modular, and remanufacturable and by offering services such as repair, reuse, refurbishment, preventive maintenance plans, product service systems, and upgrades of parts and components. Metrics suggested to monitor and track the circular economy performance of maritime OEMs are as follows:

OEM-CM 1. Advanced recycled content ratio (reused or remanufactured parts ratio by weight in products): OEM-CM 1 measures the number of remanufactured parts or components used in OEM products compared to the total number of parts or components used. This metric can be presented as a percentage or a ratio of the remanufactured parts or components by weight.

OEM-CM 2. Durability and longevity metric - lifespan of equipment: OEM-CM 2 relates to the expected lifespan of OEMs' products based on the quality, reliability, and maintainability of the parts or components used. This indicator can be expressed as the number of years or operational hours of the products compared to the industry standard or benchmark.

OEM-CM 3. Modularity, remanufacturability, and upgradability: Similar to SD-CM 2, OEM-CM 3 refers to the degree to which the products of the OEMs allow for easy removal, replacement, upgrade, or recovery of parts or components without compromising the functionality or performance of the products. Table C-2 in Appendix C presents a predefined three-level scale, for the onboard marine engine modularity score as an example.

OEM-CM 4. Lead time of remanufactured/refurbished product compared to brand-new production: This metric evaluates the time required to produce a remanufactured product compared to the time required to produce a brand-new product. OEM-CM 4 can be expressed as the number of weeks, days or hours of the lead time of a remanufactured product compared to the lead time of brand-new production as presented in Equation 5, where t_{new} and t_{reman} corresponds to lead times for new and remanufactured/refurbished products, respectively.

$$[OEM - CM\ 4] = \frac{t_{new}}{t_{reman}} \qquad \text{(Eq. 7.5)}$$

OEM-CM 5. Quality of remanufactured products: OEM-CM 5 measures the quality of the remanufactured or refurbished products, which is crucial for customer satisfaction and loyalty. This metric can be quantified as a percentage or a score using a predefined scale or criteria. For instance, Table C-3 in Appendix C provides an example of a predefined quality score scale specifically designed for an onboard marine engine.

OEM-CM 6. GHG emission reduction due to restorative operations: This indicator is concerned with the amount of greenhouse gas (GHG) emissions that are avoided or reduced by OEMs due to restorative operations such as repair, remanufacturing, refurbishment, or upgrade of parts or components, compared to the GHG emissions that would be generated by producing new parts or components. Therefore, OEM-CM 6 is characterised as a proportion of GHG emissions of carbon dioxide equivalent (CO2-eq) that the restorative operations avoid or reduce.

OEM-CM 7. Recovered waste due to restorative operations: OEM-CM 7 gauges how much waste OEMs can recover or divert from landfills as a result of restorative operations like repair, refurbishment, remanufacture, repurpose, or upgrade of parts or components, as opposed to the waste that would result from producing new parts or components. Similar to the previous metric, larger recovered waste suggests less environmental impact and more resource efficiency for the OEMs. A percentage of the waste that the restorative operations recover or divert from landfills can represent this metric.

OEM-CM 8. Circular economy marketing practices: This specific metric determines how OEMs communicate and promote their circular economy practices and products to their customers and stakeholders, such as through advertising, labelling, certification, or reporting to increase awareness. Hence, OEM-CM 8 can be formulated as a percentage or a score of circular economy marketing practises based on a predefined scale, and one example can be seen in Table C-4 in Appendix C.

OEM-CM 9. Hazardous waste generation ratio: OEM-CM 9 refers to how much hazardous waste the OEMs produce in relation to their overall waste generation. Ideally, the lower the ratio, the better for the environment and sustainability, as the metric is defined as a percentage or a ratio of the hazardous waste generated. OEM-CM 9 might also provide valuable insight into the effectiveness of waste management practices and can guide efforts towards more sustainable production processes.

OEM-CM 10. Remanufactured parts revenue compared to brand-new parts revenue: This metric compares OEMs' revenue from selling remanufactured parts or components to the revenue they make from their total sales operation, including brand-new and remanufactured parts or components. The indicator can be interpreted as the ratio of revenue generated by the remanufactured parts or components to the revenue generated by total part and component sales, including the brand-new and remanufactured parts or components.

7.5.1.3 Ship building yards (BS)

Building shipyards are the facilities where new ships are constructed using various materials, technologies, and processes. Most of them have their own design team; however, they can still work with external ship designers, depending on the project. Building shipyards can adopt circular economy principles by designing and building durable, modular, adaptable, recyclable ships that use recycled or renewable materials. Some possible circularity metrics for building shipyards are:

BS-CM 1. Modularity of vessels built: BS-CM 1 is analogous to SD-CM 2 in terms of addressing the modularity concept for vessels built at shipyards. This metric is concerned with how well the construction allows for easy removal, replacement, upgrade, or recovery of critical parts without compromising the vessel's structural integrity and in a practical manner. Table C-1 in Appendix C was initially presented for SD-CM 2, but it works equally well for BS-CM 1. Therefore, it can be used to assess the average modularity of vessels built in shipyards.

BS-CM 2. Recycled-reused material proportion by mass in ship construction: BS-CM 2 is related to the amount of recycled or reused materials consumed in ship construction processes. The indicator compares recycled or reused materials with the total materials used. The suggested metric can be expressed as a percentage or a ratio of the recycled or reused materials to the total materials consumed by mass.

BS-CM 3. Cost distribution of new, remanufactured, and reused onboard components: Parallel to SD-CM 4, the third circularity metric for building shipyards is concerned with using recovered parts and components in built vessels. Remanufactured or reused parts and components can make shipbuilding more economically viable and competitive in the long run. BS-CM 3 is the percentage of the cost of remanufactured or reused parts and components over the total cost of onboard parts and components. An increase in this metric implies more circular parts and components are included in built vessels, resulting in more circular vessels being constructed.

BS-CM 4. Durability indicator, longevity of built vessels: BS-CM 4 quantifies the expected vessel lifespan (VLS) built based on the rules and standards followed and the quality, reliability, and maintainability of the materials and components used. A longer lifespan means less need for replacement and disposal and more value extraction from the vessel. BS-CM 4 can be defined as the ratio of the average lifespan of ships to the statistically average lifespan of the same-class vessels in the world, as shown in Equation 7.6. The durability indicator is recommended to be measured annually.

$$[BS - CM\ 4] = \frac{VLS_{built}}{VLS_{world\ average}} \qquad \text{(Eq. 7.6)}$$

BS-CM 5. Ratio of customers ordering new vessels with circular products onboard: The fifth indicator represents the market's preference for and acceptance of ships that use circular products, such as recycled or remanufactured parts and components or engineering solutions based on renewable resources. Centred on the total number of customers each year, the metric can be shown as a percentage of the customers who ordered ships with circular products on board.

BS-CM 6. Ratio of hazardous waste generated: Similar to the hazardous waste metrics presented for other stakeholder groups, BS-CM 6 computes the proportion of hazardous waste that building shipyards produce in relation to overall waste production. Essentially, BS-CM 6 assesses the percentage of waste that is considered hazardous based on the overall amount of waste produced.

BS-CM 7. GHG emission reduction due to circular ship construction: BS-CM 7 is focused on how much GHG emissions the shipyard cuts down by using remanufactured, refurbished, reused, recycled, or renewable materials or other circular practices instead of the industry standard processes that would have caused GHG emissions. As a result, BS-CM 7 is defined as the fraction of GHG emissions (in CO2-eq tonnes) that are prevented due to CE principles utilised when building ships to the total GHG emissions generated during shipbuilding processes.

7.5.1.4 Ship repair yards (RS)

Ship repair yards are the facilities where existing ships are maintained, repaired, refitted, or upgraded using various materials, technologies, and processes. While some yards carry out new building and repair operations simultaneously, a considerable number are dedicated to repair only. This section will suggest nine circularity metrics for RSs to help monitor their circularity levels.

RS-CM 1. Spare parts lead time for maintenance and repairs: RS-CM 1 relates to supplying circular parts and components for repairs carried out in repair facilities. This metric is similar to OEM-CM 4, and can be defined as the ratio of the average lead time of their brand-new parts and components to the lead of their remanufactured or refurbished counterparts. The indicator value goes higher when circular parts' lead time is shorter and above 1 when it is less than brand-new products' lead time.

RS-CM 2. Proportion of reused parts in repairs: The second metric for repair shipyards gives an indication of the percentage of reused parts in repair operations. RS-CM 2 can be defined as the ratio of different units, such as monetary value, weight, or number of parts. For simplicity, this research sticks to the number of parts reused over the total number of parts used in repairs.

RS-CM 3. Proportion of reused parts in maintenance: RS-CM 3 is analogous to RS-CM 2, except this indicator concerns maintenance operations, which are different from repairs. Maintenance includes replacing parts and components before they fail, and torn and worn parts are also involved. So, RS-CM 3 is identified as the ratio of reused parts over the total number of parts replaced in maintenance operations.

RS-CM 4. Volume of returns: This metric concerns the reverse supply chain part or circular practices. All removed core parts should be returned to a remanufacturing facility in a fully circular system. RS-CM 4 indicates the return performance in that sense, so it is defined as the ratio of the number of returned cores over the total number of cores removed during ship repair operations.

RS-CM 5. Quality of returns: Similar to the previous one, RS-CM 5 also relates to the reverse supply chain. This measurement reflects the quality of cores returned to a remanufacturing facility, as not all can be remanufactured. Core parts below an acceptable quality threshold are ruled out. Therefore, RS-CM 5 is expressed as the ratio of good-quality cores sent to the remanufacturer over the total number of cores sent.

RS-CM 6. Circular revenue generated: RS-CM 6 is dedicated to the financial outcomes of circular economy practices. This indicator focuses on the proportion of parts and component sales related to circular practices over total parts and component sales revenues. Another point of view would be the profit-based comparison of circular revenue and total revenue in a specific time period.

RS-CM 7. Ratio of customers who purchased circular parts and components: Parallel to BS-CM 5, this metric measures customer (ship owner or operator) involvement in circular practices in repair shipyards. RS-CM 7 is the ratio of the number of customers charged for reused, remanufactured, or refurbished parts to the number of total customers served.

RS-CM 8. Ratio of hazardous waste generated: RS-CM 8 is similar to hazardous waste metrics in previous stakeholder groups. This case, however, focuses on the hazardous waste generated by ship repair facilities, comparing the quantity of hazardous waste produced with the overall waste generated during the facility's operations.

RS-CM 9. GHG emission reduction due to circular options: This metric aligns with similar emission reduction indicators introduced for other stakeholders in this section. RS-CM 9 evaluates the percentage of GHG emissions that repairing shipyards prevents or mitigates as a result of using circular practices.

7.5.1.5 Classification societies (CS)

Classification societies are organisations that establish and apply technical standards for the design, construction, and operation of ships and provide certification and inspection services to verify the compliance of ships with those standards. Classification societies can support circular economy principles by setting and enforcing standards that promote ships' durability, modularity, adaptability, and recyclability and reduce the environmental impact while increasing the social responsibility of ship operations. Some possible circularity metrics for classification societies are:

CS-CM 1. Having rules, standards, or regulations regarding remanufactured components: CE is an emerging topic in the maritime industry, and due to its highly regulated nature, the maritime domain cannot adapt to changes promptly. Classification societies' rules and standards can be updated to include guidelines for using remanufactured components and promoting circularity in shipbuilding and maintenance. Therefore, CS-CM1 links classification society guidelines to remanufactured onboard marine components and indicates whether they have defined rules, as shown in Table C-5 in Appendix C.

CS-CM 2. Having rules, standards, or regulations regarding refurbished equipment: CS-CM2 parallels the previous metric, CS-CM 1. However, the difference is that while CS-CM 1 focuses on remanufactured parts, this metric focuses on refurbished electronics, including computers, communication or navigation equipment, etc. CS-CM2 assesses whether a classification society has established rules, standards, or regulations specifically for refurbished electronics used in shipbuilding and maintenance. It complements CS-CM1, which evaluates the guidelines for remanufactured components in the maritime industry. Table C-5 in Appendix C can easily be adapted to address CS-CM 2.

CS-CM 3. Having a standard process for certifying circular products: CS-CM 3 focuses on the remanufactured or refurbished equipment certification process. Each part, component, or piece of equipment used onboard classed vessels is subject to approval (certification) from their classification society. The certification requirement is the same for circular products, so CS-CM 3 measures whether classification societies have rules regarding the certification process of circular marine equipment. The corresponding rating scale is provided in Table C-6 in Appendix C.

CS-CM 4. Number of type approval tests for circular products: CS-CM 4 measures the percentage of type approval tests that classification societies conduct specifically for remanufactured, refurbished, reused, recycled, or, in general, circular products. The metric evaluates the extent to which classification societies actively ensure the quality and compliance of circular marine equipment and the reliability of circular products used onboard classed vessels. The metric is the ratio of the total number of type approval certificates granted for circular products to the total number of type approval certificates granted.

CS-CM 5. Having rules, standards, incentives, or regulations regarding improving the reverse supply chain for onboard assets at the decommissioning stage: CE cannot be achieved without a properly functioning reverse supply chain (Okumus et al., 2024b) and CS-CM 5 purely concentrates on this part and relates to any rules, standards, regulations, or incentives they include for enabling a closed-loop chain. Similar to the previous metrics, a three- or four-level predefined scale (such as Table C-5 in Appendix C) can be adapted to measure the CS-CM 5 score.

7.5.1.6 Ship owner or operators (OO)

Ship owners or operators are the entities that own or operate the vessels and that make decisions about the chartering, cargo, fuel, route, speed, port, and other aspects of the operation. Ship owners or operators can adopt CE principles by acquiring and operating circular ships, choosing circular onboard equipment, and contributing to the reverse supply chain. Some possible circularity metrics for ship owners or operators are suggested below.

OO-CM 1. Longevity of their fleet: OO-CM 1 directly indicates OO's fleet lifespan and compares it with the world fleet. This metric is defined as the ratio of the average recycling age of OO's fleet to the world's average ship recycling age. This metric considers realised numbers as its focus, not the expected or designed life of assets; therefore, the age of the vessels sent to ship recycling facilities is compared with the world average for each ship owner or operator.

OO-CM 2. Circularity of operation and maintenance: OO-CM 2 relates to the ship operation and maintenance (O&M) stage in a vessel's lifespan. This indicator is precisely defined as the percentage of total circular parts (e.g., remanufactured, refurbished, or reused) in total parts and components used in the O&M stage.

OO-CM 3. Circularity of design and shipbuilding: The third metric focuses on the circularity of design and shipbuilding. OO-CM 3 gives an idea of the extent to which sustainable and circular principles are incorporated into the design and construction of a vessel. It mainly measures the use of circular materials by mass in the shipbuilding process.

OO-CM 4. Contribution to the Reverse Supply Chain: Volume of returns: OO-CM 4 is analogous to RS-CM 4. However, in this case, the number of returned cores is calculated for each ship owner or operator company rather than shipyards. OO-CM 4 is the percentage of core parts and components returned to a remanufacturing facility to the total number of parts and components removed from a ship owner's vessels.

OO-CM 5. Contribution to the Reverse Supply Chain: Quality of returns: OO-CM 5 parallels RS-CM 5. The difference is that the core numbers are calculated considering ship owner or operator company assets. The metric is defined as the ratio of the number of good-quality cores sent back to remanufacturers over the total number of cores sent.

OO-CM 6. Ratio of solid waste generated during the decommissioning phase: OO-CM 6 aims to capture how much waste is generated at the end-of-life stage of vessels for ship owners. Therefore, the indicator is expressed as the percentage of total waste generated (W_{total}) related to vessels' light displacement tonnes (LDT_{vessel}), or, in other words, the total weight of the ship's hull, machinery, structure, fittings, and onboard equipment as given in Equation 7.7.

$$[OO - CM\ 6] = \frac{W_{total}}{LDT_{vessel}} \qquad \text{(Eq. 7.7)}$$

OO-CM 7. Ratio of hazardous waste generated during the decommissioning phase: In line with hazardous waste metrics for other stakeholder groups, OO-CM 7 targets the ratio of hazardous waste to total waste generated during the end-of-life stage for ship owners.

OO-CM 8. Ratio of solid waste generated during the repair or refit operations:

OO-CM 8 is parallel to OO-CM 6, but this metric focuses on the repair and refit activities rather than the decommissioning operations. As such, it can be defined as the ratio of total solid waste generated during repair or refit operation to light displacement tonnage of the vessel.

OO-CM 9. Ratio of hazardous waste generated during the repair or refit operations: OO-CM 9 is parallel to OO-CM 7. While both metrics measure the ratio of hazardous waste generated, OO-CM 9 specifically focuses on the waste generation during repair or refit operations.

7.5.1.7 Recycling facilities (RF)

Ship recycling facilities are specific facilities equipped to dismantle and recycle end-of-life ships. These facilities have the necessary infrastructure and capabilities to handle hazardous materials and ensure the proper disposal or recycling of various ship components safely and efficiently. Ship recycling facilities are crucial in transitioning to a circular maritime industry, as CE heavily relies on a closed-loop supply chain (Okumus et al., 2023b). Some key circularity metrics for the recycling facilities are suggested as follows:

RF-CM 1. Circular revenue generated: RF-CM 1 is analogous to RS-CM 6 in highlighting the financial outcomes of CE principles and the reverse supply chain. However, this time, the metric is defined as the proportion of revenue from selling core parts to remanufacturers over the total revenue from ship recycling.

RF-CM 2. Value retention due to reuse, remanufacturing, and repurposing: Aligned with the previous metric, RS-CM 2 dives further into the approximate value retention due to circular practises enabled by RFs core parts collection efforts. Indeed, this metric is defined as the ratio of estimated value retention to the acquisition price of corresponding end-of-life vessels.

RF-CM 3. GHG reduction due to material recovery at end-of-life: Like other GHG reduction indicators for other stakeholders, RF-CM 9 also aims to calculate the percentage of GHG emissions that recycling facilities mitigate thanks to the reverse supply chain and circular economy principles.

RF-CM 4. Ratio of solid waste generated during the decommissioning phase: RF-CM 4 is designed to indicate the amount of solid waste generated during the decommissioning phase of vessels. It measures the ratio of total solid waste produced to the LDT of the vessel decommissioned.

RF-CM 5. Solid waste reduction due to restorative EoL processes: As a complement to the previous metric, RF-CM 5 relates to waste reduction due to circular practices in ship recycling facilities. The indicator is defined as the percentage of solid waste reduction from advanced circular economy practices, such as remanufacturing and refurbishing, to the total waste generated during the end-of-life stage.

RF-CM 6. Ratio of hazardous waste generated during the decommissioning phase: RF-CM 6 parallels previous hazardous waste metrics defined for other stakeholders. Similarly, this indicator points out the ratio of hazardous waste generated to total solid waste generated in ship recycling facilities.

RF-CM 7. Volume of returns: The reverse supply chain essentially depends on recycling facilities. Hence, recycling yards' systematic core collection and return performance are critical. At this point, RF-CM 7 is centred on the quantity of returns, which is defined as the ratio of the number of returned core parts to the total parts removed during the EoL phase.

RF-CM 8. Quality of returns: RF-CM 8 complements the quality aspect of the returned core parts and components. As mentioned in several other stakeholder groups, the quality of return indicator is defined as the percentage of acceptable or good quality returned cores to the total number of cores returned to a remanufacturing or refurbishing facility.

7.5.1.8 Cargo owners (CO)

Cargo owners are end customers of maritime transportation operations. They own or produce large ranges of goods transported by ships, such as raw materials, intermediate commodities, or final products. Their role in the maritime industry's circular transition is mainly associated with their (circular) vessel choices.

CO-CM 1. Circular freight ratio: Currently, cargo owners tend to stick with younger vessels available mainly due to insurance practices. On the other hand, the CE concept can improve the lifespan of vessels and onboard equipment, which brings a conflict of interest, especially when the insurance perspective is added to the equation. At this point, CO-CM 1 is defined to help cargo owners by providing a specific indicator to measure the circularity level of their maritime transportation. The metric is defined as shown in Equation 7.8.

$$[CO - CM\ 1] = \frac{(W_{cargo} * distance)_{circular}}{(W_{cargo} * distance)_{total}} \quad \text{(Eq. 7.8)}$$

Where W_{cargo} stands for the weight of cargo carried, while *distance* is the nautical miles they are carried. Thus, the indicator reveals a weighted usage of circular vessels over the total maritime transportation service provided for cargo owners. By doing so, this metric can assist cargo owners in making more sustainable vessel choices that align with circular economy principles. By considering the circular freight ratio, cargo owners can contribute to reducing environmental impact and promoting a more sustainable maritime industry.

CO-CM 2. Reuse or recycle rate of packaging: CO-CM 2 focuses on packaging reuse or recycle rate in maritime transportation. This metric measures the extent to which packaging materials are reused or recycled instead of being disposed of after use. By tracking this rate, cargo owners can assess their circularity performance and identify opportunities for improvement in their packaging practices. This metric aligns with the circular economy concept by promoting waste reduction and efficient use of resources in the maritime industry.

7.5.1.9 Local or international authorities (AUT)

Authorities are the entities that set and enforce rules and standards for the maritime industry. Flag states, port states, and the International Maritime Organisation (IMO) can be examples of such entities. Safety, security, environmental protection, taxes, or local workforce regulations are some areas they can cover. Local or international authorities can adopt or promote CE principles by creating and implementing policies and regulations and by incentivising circularity in the maritime domain by monitoring its performance and impact. Some possible circularity metrics developed for that purpose within this study are as follows:

AUT-CM 1. Having standards or regulations regarding remanufactured marine equipment: AUT-CM 1 is related to whether an authority has any enforcement or guidelines for remanufactured equipment onboard vessels. This metric can be defined as a yes-or-no scale.

AUT-CM 2. Having standards or regulations regarding refurbished electronics onboard: Analogous to the previous indicator, AUT-CM 2 concerns regulations, standards, or guidelines for refurbished electronics, such as computers, navigation equipment, control panels, etc., onboard. Similarly, AUT-CM 2 is designed as a yes-or-no scale.

AUT-CM 3. Providing incentives for circular economy practices for vessels at the EoL stage: AUT-CM 3 focuses on whether there are incentives to encourage circular economy practices for vessels at the end-of-life stage. This could include initiatives such as recycling programmes, responsible disposal methods, or financial incentives for sustainable practices. The purpose of AUT-CM 3 is to assess the extent to which the industry promotes environmentally friendly practices during vessel decommissioning and disposal.

AUT-CM 4. Defining a circular vessel to create a baseline standard: AUT-CM 4 aims to clearly define what constitutes a circular vessel to establish a baseline standard for the industry. This will help ensure that all stakeholders understand the principles and criteria that need to be met for a vessel to be considered circular. By setting this standard, it will be easier to track progress and identify areas for improvement regarding circularity within the industry.

When a combination of maritime stakeholders is considered, more complex KPIs can be formed, or existing ones in the literature can be adapted to the maritime. For instance, the circular economy index (CEI) developed by Di Maio and Rem (2015) can be utilised if recycling shipyards, OEMs and building shipyards work together and share the financial aspect of their circular operations. However, in practice, divided stakeholder structure in the sector does not make it easy to calculate inter-stakeholder metrics. Therefore, the author has focused on tailor-made stakeholder-based circularity indicators in this section. When maritime stakeholders monitor their circular performance and start improving their circularity levels, the industry will benefit from five main aspects. The next section will focus on those aspects as they will show the overall results and impacts of improving each stakeholder condition in the industry.

7.5.2 Major Industry Aspects

Almost every study on circular economy metrics, whether they are proposing new metrics or examining existing metrics in the literature, has linked the metrics with three sustainability dimensions: economic, environmental, and social aspects. Some notable examples of studies linking the metrics with the three sustainability pillars include Calzolari et al. (2022)'s systematic literature review on CE indicators for supply chains, which listed descriptions and occurrences of metrics in each pillar; Di Maio et al. (2017)'s market value approach that proposed a value-based resource efficiency indicator; Mesa et al. (2018)'s study that listed conventional indicators according to the three pillars; Kravchenko et al. (2019)'s screening of leading sustainability related indicators that started with 665 papers and resulted in 52 fully-read publications; and De Pascale et al. (2021)'s systematic review that maps CE indicators in the three pillars. Furthermore, several studies have pointed out that CE supports a significant number of UN Sustainable Development Goals (SDGs): According to Ortiz-de-Montellano et al. (2023), CE mostly helps with SDGs 8 (decent work and economic growth), 12 (responsible consumption and production), and 13 (climate action). Schroeder et al. (2019), on the other hand, found that CE has a strong connection with SDGs 7 (affordable and clean energy), 8, 12, and 15 (life on land). This occurs due to the intertwined relationship between CE and sustainability.

However, Kristensen and Mosgaard (2020) concluded that CE does not hit all three aspects equally. Calzolari et al. (2022) have grouped CMs into 20 of the most commonly employed metric categories, such as separate waste and emissions, supply chain elements, etc., which diversifies the impact spectrum. Ibáñez-Forés et al. (2022) provided practical insights by identifying 10 CE categories in CSRs, focusing on aspects like raw material consumption, suppliers, waste and emissions, independently. Therefore, this section presents more balanced industry aspects of CE for the maritime industry than traditional sustainability dimensions. Specifically, financial, supply chain, material requirements, waste and emissions, and social perspectives. Also, in the metric validation step explained in Section 7.3.3, the above industry aspects have been discussed with the participants during the semi-structured stakeholder interviews and agreed upon. This section briefly expresses how circularity indicators would enhance these aspects for the maritime stakeholders in this research's scope.

Circular economy practices within the maritime industry have the potential to revolutionise traditional business models and affect financial viability. Circularity metrics facilitate identifying and exploiting new revenue streams by reusing and remanufacturing maritime assets. Measuring circular revenue for maritime stakeholders can provide valuable insights into the financial benefits of adopting circular practices, ultimately leading to more sustainable and profitable operations. By quantifying the potential revenue generated from circular strategies, stakeholders can make informed decisions that prioritise both economic growth and environmental sustainability. Moreover, offering circular services emerges as a lucrative business model, fostering investment in local actions and promoting a transition towards a circular economy. This aligns with the broader financial benefits highlighted in the literature, such as cost saving opportunities (Kerin & Pham, 2020) and enhanced profitability (Abbey et al., 2018) through circular business models. Having remanufactured or refurbished parts would provide a competitive advantage in the maritime industry by reducing costs and increasing overall efficiency, as demonstrated in a main engine remanufacturing case study by Okumus et al. (2023c). Additionally, it would contribute to a more sustainable business model that aligns with growing environmental concerns and regulations.

CE practices in the maritime industry can help maritime companies improve the closed-loop supply chain. The CE principles can help companies with a more resilient supply chain with further reuse and remanufacture strategies, diversifying sourcing (remanufactured vs. new products), and reducing dependence on finite resources (reusing or recycling). The availability of options such as remanufactured and new products will create advantages such as a reduction in lead time. Moreover, the CE approach encourages the use of standardised components and modularity in product design, which will diversify the options of available parts and products in the supply chain. By identifying potential supply chain risks and vulnerabilities, companies can develop strategies to mitigate them and ensure continuity of operations.

One of the main direct environmental perspectives is raw material requirements, which can be evaluated and improved upon through the implementation of advanced CE principles. For instance, the shipbuilding industry consumes vast amounts of low carbon steel and aluminium. Depending on the design, various steel grades can be preferred, such as ASTM A572 Grade 42 (ASTM, 2017) or ASTM A131 Grade EH36 (ASTM, 2019), which results in critical raw material (as defined by the European Commission (2023)) consumption such as manganese, nickel, copper, chromium, and tungsten (Chernyshov et al., 2016). The emphasis on recycled content and the longevity of maritime assets reduces the dependency on virgin materials, addressing material scarcity and environmental degradation. The holistic CE approach not only benefits the environment but also enhances overall supply chain resilience and efficiency. By identifying related circularity metrics and enabling regular monitoring, the research underscores the importance of material recovery and cascading uses, which conserve resources and mitigate the environmental impact associated with raw material extraction and processing. By prioritising the recovery and reuse of materials, the maritime industry can significantly lower its environmental footprint, contributing to global efforts to combat climate change. The metrics encourage the adoption of cleaner, more efficient processes that reduce the industry's impact on natural resources and promote a healthier ecosystem. Emphasising environmental sustainability through circular practices aligns with international environmental standards and regulations and improves the maritime industry's position in the greater transportation domain.

Furthermore, restorative circular practices help mitigate waste and emission generation, including emissions due to manufacturing energy consumption. Regenerative recycling processes have a lower absolute CO_2 footprint compared to brand-new manufacturing. In the maritime industry, decarbonisation is usually associated with the operation; and manufacturing or recycling processes are currently ignored. On the other hand, there is a vast potential for emission reduction within the industry if the CE principles are applied (Afrinaldi et al., 2017). Considering the impact of emissions, CE is the only way to achieve cradle-to-cradle decarbonisation in the maritime industry. Moreover, companies can minimise their total waste generation through various strategies (e.g., hazardous waste identification and segregation, transparency, and labelling). CE principles and metrics will provide the necessary data to track progress and make informed decisions to achieve sustainable waste management and emissions reduction goals, ultimately promoting a more environmentally responsible and efficient maritime industry.

Making the circular transition measurable allows stakeholders to identify key points to focus on for a more circular maritime industry. Due to the fact that CE enables fostering job creation, enhancing community relations, and promoting health and safety standards (Repp et al., 2021), a clear strategy for transitioning to a circular maritime industry will lead to these social benefits being realised sooner and with greater impact. The adoption of circular economy principles supports the development of a skilled workforce, as advanced circular practices require, ready to tackle the challenges of sustainable maritime operations. It also encourages the maritime industry to engage in more responsible practices, focusing on social equity and community well-being.

Moreover, circular practices such as remanufacturing can be designed in line with recent localisation trends in the manufacturing industry. Which, in return, would create new skilled job opportunities where a skilled workforce is intended. In addition, when adopted, the metrics will significantly increase awareness of CE in the maritime domain. Awareness and stakeholder perception of such advances are critical to a successful transition, and social sustainability is essential for long-term success in the industry. By prioritising social equity and community well-being, the maritime industry can improve its environmental impact and contribute positively to society. This shift towards responsible practices can lead to a more sustainable and prosperous future for all stakeholders.

7.6 Case Study on Ship Repair Yards

7.6.1 Introduction to the Case Study

This case study aims to demonstrate how the circularity metrics developed for the maritime industry can be practically applied. Through a particular focus on ship repair yards, this investigation aims to assess the utilisation of these metrics in enhancing CE practices, improving sustainability, and reducing environmental impact. This study is significant as it offers practical insights into the application of circularity metrics in the maritime industry, validating the theoretical framework presented in previous sections. The study was carried out at three private repair shipyards in Turkey, chosen for their active engagement in sustainable practices and openness to embracing new metrics for assessment.

The shipyards preferred to remain anonymous and were therefore named Shipyards A, B, and C, respectively. Table 7-3 below illustrates their facility and operational details. The case study involved analysing the shipyards' material flows, energy consumption, and waste generation to calculate their circularity performance. The study results showed that all shipyards had significant room for improvement in terms of resource efficiency and waste reduction.

Table 7-3: Shipyard facility and operational details.

	Facility Details			
	Location	**Total facility area**	**Dock details**	**Ship repair capacity**
Shipyard A	Marmara Region, Turkey	105,000 m2	3 floating docks: Suexmax, Panamax, Handymax	4,500,000 DWT per annum
Shipyard B	Marmara Region, Turkey	90,000 m2	1 graving dock up to Suezmax-Capesize, 2 floating docks up to Handymax	3,000,000 DWT per annum

	Facility Details			
	Location	Total facility area	Dock details	Ship repair capacity
Shipyard C	Marmara Region, Turkey	60,000 m2	1 graving dock up to Panamax size	1,000,000 DWT per annum

Considering material circulation from repair and maintenance activities, the author selected ship repair yards to demonstrate the metrics in a real-world setting and highlight the potential for circularity improvements in shipyards' operations. Ship repair yards were specifically chosen to showcase how circular economy principles can be applied to existing operations and merchant fleets rather than solely focusing on new construction projects. Since the circular transition is in its earlier stages for the maritime industry and ship recycling facilities have not established a sufficient infrastructure to enable data collection, focusing on repairing shipyards has seen more immediate and tangible results regarding sustainability and efficiency improvements. Comparing Shipyards A, B, and C's individual performances and understanding the factors resulting in the different outcomes paves the way for sharing best practices and recognising high-performing facilities and organisations in terms of CE. The case study findings will offer valuable insights for shipyards seeking to improve their circularity performance in the future.

7.6.2 Case Study Steps and Findings

An eight-step application plan has been devised for the case study, as depicted in Figure 7-4. The plan includes introducing the circularity concept, carrying out baseline assessments, setting specific circularity targets, enabling CE performance calculation, and monitoring progress to continuously improve repair shipyard operations. By following these steps, the shipyards can identify areas for improvement and gradually increase their circularity performance, contributing to a more sustainable maritime industry.

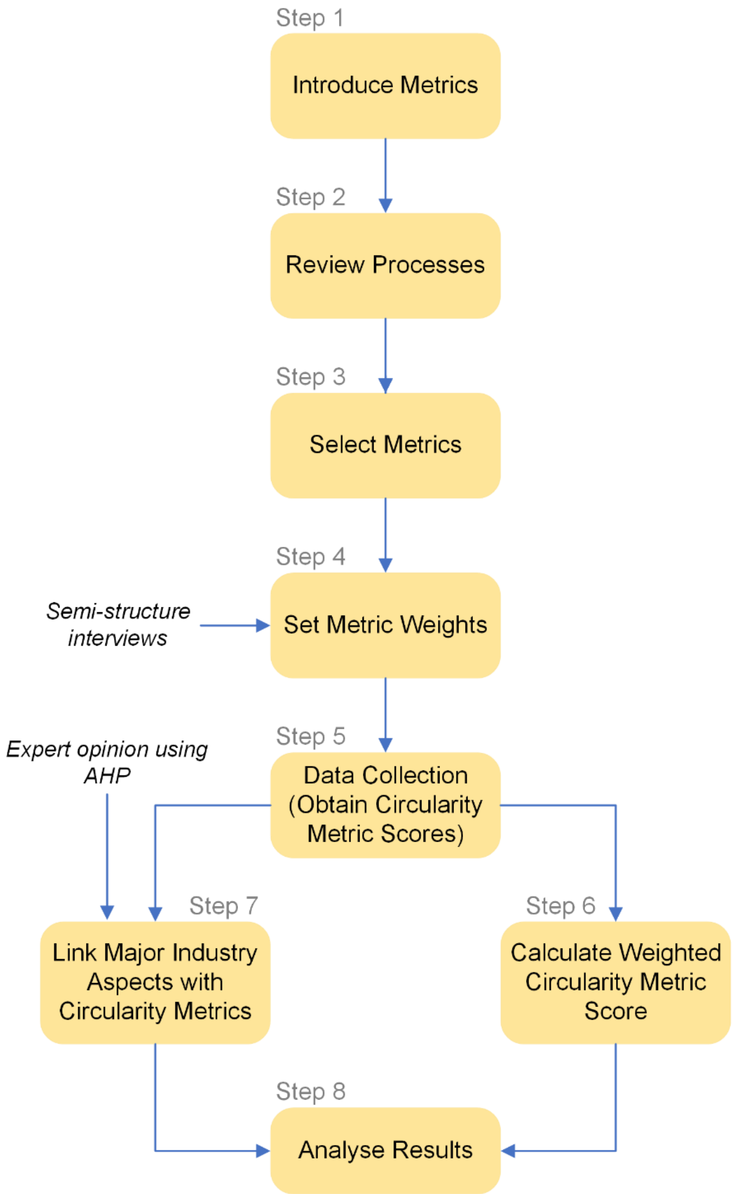


Figure 7-4: Case study steps.

Step 1: Introducing the metrics to shipyard managers and their technical or engineering teams. The research objectives were outlined, and the proposed metrics were introduced to participants from the shipyards. This step ensured all stakeholders were aware of the study's goals and the importance of each metric.

Step 2: The author of this research examined each shipyard's general ship repair process flows and discussed them with their engineering staff to capture shipyards' internal processes and ensure the same scope is set for each facility.

Step 3 (Metric selection): In this step, considering data availability or other factors preventing transparent information sharing, some metrics can be excluded before assigning the importance levels. However, since shipyards remain anonymous and are willing to learn their circularity levels, it was decided that all suggested metrics (from RS-CM 1 to RS-CM 9) should be included in this case.

Step 4: Defining metric importance levels (weights): It is essential to incorporate industry opinion and perspectives at this step to ensure that the selected metrics fully reflect the priorities and challenges faced in the selected stakeholder business. To accomplish this, the research team organised separate meetings with each shipyard (A, B, and C) to discuss and gather insights on the selected metrics. In these meetings, professionals from each shipyard got acquainted with the circularity metrics included in the case study. Following this, the author conducted semi-structured discussions to determine if uniform weights could accurately represent the importance of each metric based on real operations in shipyards. The participants unanimously agreed that the metrics for reused parts (RS-CM 2 and 3) held the highest importance. Next in importance were the metrics related to volume (RS-CM 4) and quality (RS-CM 5) in the reverse supply chain. Lastly, the circular revenue metric (RS-CM 6) was identified as the least significant in importance. This feedback was then consolidated to determine the final importance levels displayed in Table 7-4. Before proceeding, the research team presented the final weights to Shipyards A, B, and C, who approved and agreed upon the final table.

Table 7-4: Repair shipyard circularity metric weights assigned.

	Metric weight
RS-CM 1	10.0%
RS-CM 2	15.0%
RS-CM 3	15.0%
RS-CM 4	12.5%
RS-CM 5	12.5%
RS-CM 6	5.0%
RS-CM 7	10.0%
RS-CM 8	10.0%
RS-CM 9	10.0%
Total	**100.0%**

Step 5: The fifth step is gathering data from ship repair yards. It is the main stage for the participants, where they provide fundamental information to calculate the circularity metrics. This step can take a couple of weeks, depending on the existing shipyard records or data availability in general. To make things easier and more effective, the author prepared an online questionnaire (disclosed in Appendix D), and considering their 2023 business results, three shipyards provided their circularity scores using the metric definitions in Section 7.5.1.4. When needed, the author supported the shipyard professionals who had to dive into their organisations' operational and financial year-end figures to calculate the requested metrics.

Step 6: Considering the information provided by the shipyards (in Step 5) and the metric importance levels obtained (in Step 4), the next step involves calculating the performance scores for each shipyard based on the metrics selected. This will allow for a comprehensive evaluation of each shipyard's performance in relation to the established criteria. The results are illustrated in Table 7-5 and Figure 7-5. While the former presents the scores each shipyard (A, B, and C) has according to the circularity metrics (RS-CM 1 to 9), the latter explicitly provides a radar chart to show each facility's performance.

Shipyards B, A, and C have total circularity scores of 54.88, 43.00, and 37.00, respectively. Comparing their CM scores at individual levels reveals that no single shipyard fully dominates others, meaning Shipyard A and Shipyard C excelling in some metrics as well.

All three facilities scored highly on the lead time metric (RS-CM1); Shipyard A scored 80, while Shipyards B and C scored 70 each. This result indicates that the availability of circular spare parts has reached a certain level. Despite Shipyard A's more efficient supply of circular spare parts, its performances in RS-CM 2 and RS-CM 3 suggest a limitation in reflecting this efficiency in repair and maintenance operations, lagging in reused part ratios. Furthermore, the metric for customers provided with circular parts (RS-CM 7) reinforces this observation, revealing a significant disparity in scores between Shipyard B (80) and Shipyard A (30).

Shipyard B excelled and achieved the highest score in key areas such as providing customers with circular parts (RS-CM 7), utilising reused parts in repair (RS-CM 2) and maintenance (RS-CM 3) operations, and returning end-of-life core parts and components to remanufacturer facilities (RS-CM 4). These metrics reflect Shipyard B's significant commitment to advancing the circular economy. The financial metric RS-CM 6 further highlights this scenario, indicating that 70% of their revenue is derived from circular products, in contrast to 60% for Shipyard C and a mere 40% for Shipyard A. Shipyards A and B are particularly comparable in terms of their total facility areas and dry and floating dock capacities. However, all the above factors result in the huge gap between Shipyards A and B's circular revenue ratios.

Upon examining the reverse supply chain metrics, specifically RS-CM 4 for volume and RS-CM 5 for the quality of returns, a perfectionist pattern was observed from Shipyard A. While Shipyards B and C return 65 and 50 percent of used cores, half of what they sent is found remanufacturable; Shipyard A returns only 10% of the cores, and 90% of what they sent is remanufactured. Shipyard A's perfectionist approach stands out as a key factor hindering its progress. However, this can be transformed into a quick win through a decisive waste management strategy change, which could also elevate their score in emission reduction through circular practices (RS-CM 9).

Table 7-5: Circularity metric scores for Shipyards A, B and C.

Circularity Metrics (CM)	Metric weight	CM Scores (CMS) over 100 points			Weighted CM Scores		
		Shipyard A	Shipyard B	Shipyard C	Shipyard A	Shipyard B	Shipyard C
RS-CM 1	10.0%	80	70	70	8.00	7.00	7.00
RS-CM 2	15.0%	50	70	70	7.50	10.50	10.50
RS-CM 3	15.0%	20	30	10	3.00	4.50	1.50
RS-CM 4	12.5%	10	65	50	1.25	8.13	6.25
RS-CM 5	12.5%	90	50	50	11.25	6.25	6.25
RS-CM 6	5.0%	40	70	60	2.00	3.50	3.00
RS-CM 7	10.0%	30	80	10	3.00	8.00	1.00
RS-CM 8	10.0%	65	40	5	6.50	4.00	0.50
RS-CM 9	10.0%	5	30	10	0.50	3.00	1.00
	100.0%				**43.00**	**54.88**	**37.00**
					TOTAL CIRCULARITY SCORES		

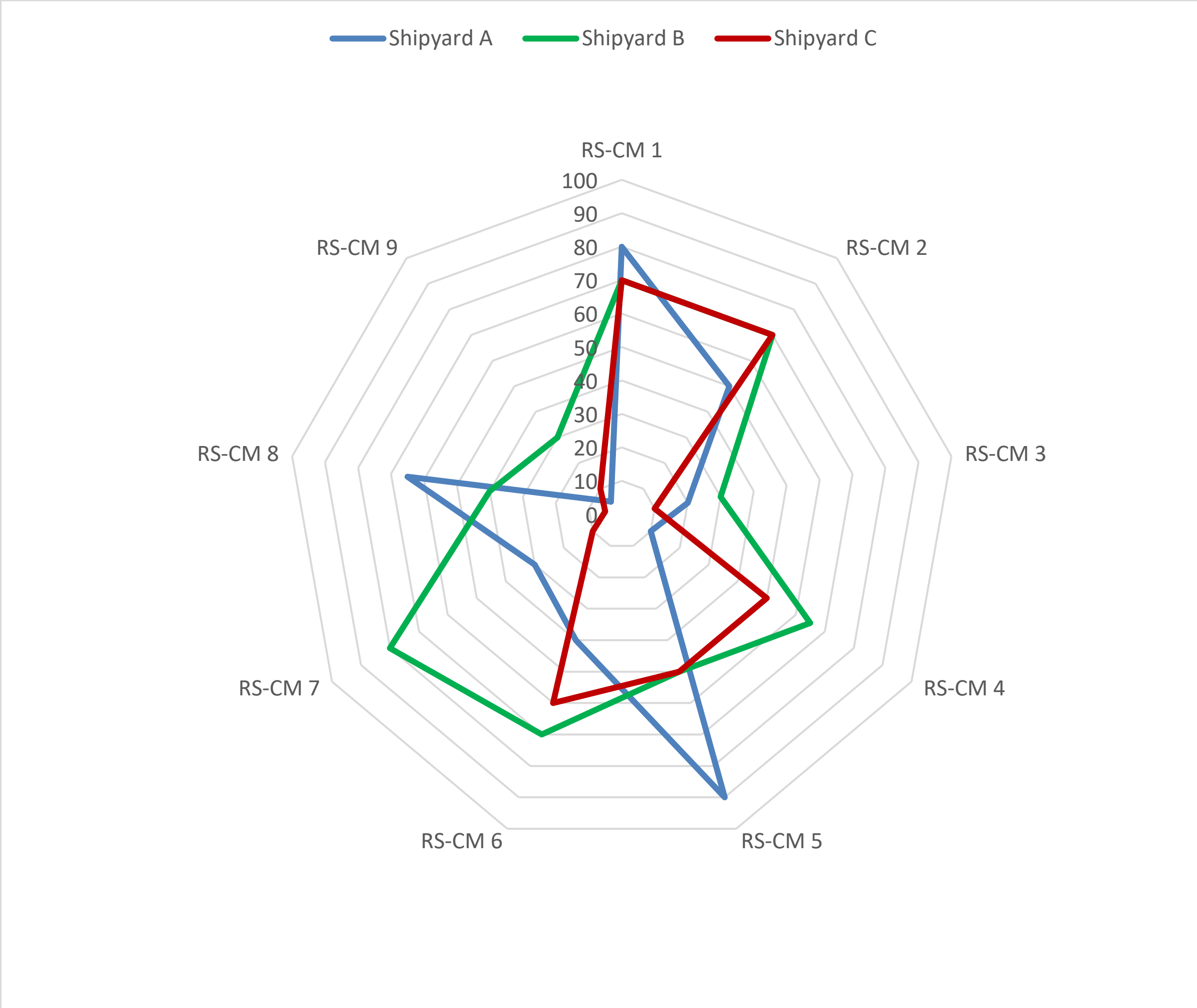


Figure 7-5: Shipyards' performance on each circularity metrics.

The final two steps of the case study involve a comprehensive analysis of the findings. As a part of this analysis, the strengths and weaknesses of each shipyard in terms of circularity performance will be identified. Additionally, recommendations for improvement will be provided based on the results obtained.

Step 7: Considering the five dimensions explained in Section 7.5.2 (financial, supply chain, raw material consumption, waste and emissions, and social aspects), the connection between the circularity metrics and the five industry aspects has been investigated. Five experts from the maritime industry were selected to determine the relationship between the metrics and the five aspects. **Table 7-6** shows the experts' background and experience in the maritime industry, highlighting their qualifications for evaluating the relationship. The traditional linear analytic hierarchy process method (Saaty, 1980) was chosen due to its proven effectiveness in decision-making processes, and calculations were executed using Goepel (2013)'s template to derive the importance weights for each metric across the five dimensions. Each expert has assessed ten pairwise comparisons for each rated circularity metric involved; therefore, 90 comparisons per expert were scored using a 1–9 Likert scale to address the connection. *Figure C-1* in Appendix C presents an example assessment form used in this stage. The final results of this process are provided in Table 7-7. Based on the AHP results, the nine circularity metrics in this case study demonstrate a relatively even representation across the five aspects as depicted in Figure 7-6. The material requirement aspect demonstrates the highest association at 24.4%, whereas the social aspect reveals the lowest association at 16.7%. Upon closer examination of individual aspects, it is evident that each aspect column is highly associated with at least one circularity metric. Furthermore, the aspect columns in Table 7-7 provide detailed information about the association of metrics with each aspect and the degree of association.

Table 7-6: The experts' background.

	Industry Experience	Background
Expert 1	13 years	Naval Architect, operations manager of shipyard
Expert 2	18 years	Captain, MSc, PhD
Expert 3	21 years	Naval Architect, Classification society
Expert 4	15 years	Marine Engineer, MSc
Expert 5	17 years	Naval Architect, PhD

Table 7-7: Major industry aspects and circularity metrics connection levels.

	Major Industry Aspect Connection Levels (ACL)				
Circularity Metrics	**1- Financial**	**2- Supply Chain**	**3- Material Requirement**	**4- Waste & Emissions**	**5- Social**
RS-CM 1	29.1%	42.3%	18.1%	6.7%	3.7%
RS-CM 2	32.9%	4.8%	46.2%	9.1%	7.1%
RS-CM 3	39.2%	5.9%	36.7%	11.7%	6.6%
RS-CM 4	6.8%	39.1%	31.8%	13.3%	8.9%

	Major Industry Aspect Connection Levels (ACL)				
Circularity Metrics	**1- Financial**	**2- Supply Chain**	**3- Material Requirement**	**4- Waste & Emissions**	**5- Social**
RS-CM 5	7.3%	34.8%	36.2%	11.3%	10.4%
RS-CM 6	54.5%	5.1%	23.4%	9.2%	7.8%
RS-CM 7	10.7%	10.2%	16.1%	11.0%	52.0%
RS-CM 8	9.1%	6.0%	5.8%	53.3%	25.9%
RS-CM 9	6.0%	5.7%	5.7%	54.4%	28.2%
Σ Aspect Weights	195.6%	153.9%	220.0%	180.0%	150.6%
Normalised Weights	**21.7%**	**17.1%**	**24.4%**	**20.0%**	**16.7%**

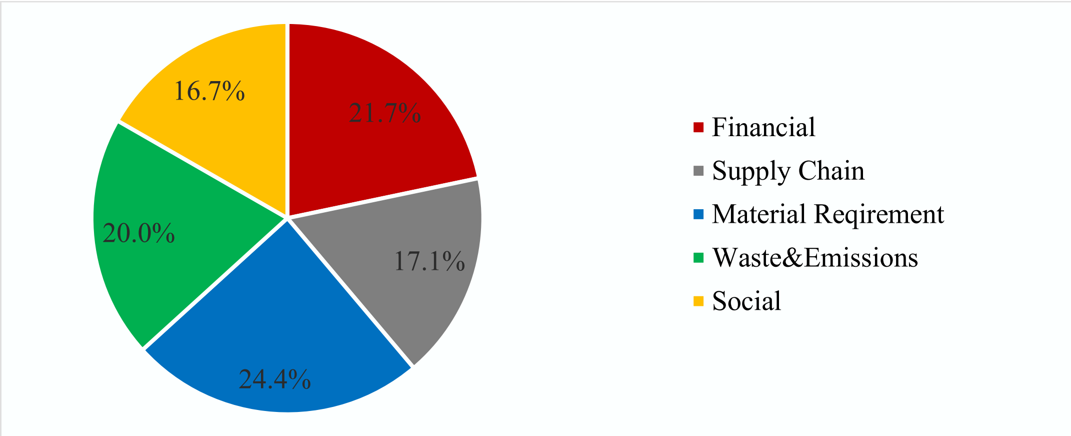


Figure 7-6: Aspect connection levels of ship repair yard circularity metrics.

Step 8: Combining the outcomes of Step 7 and Step 5, the participant organisations' performance levels on the five aspects have been obtained using Equation 7.9 below**.** The results, depicting the performance of each shipyard based on the developed circularity metrics, are illustrated in **Figure 7-7.**

$$PS_{i,j} = \frac{\sum_k (ACL_i * CMS_j)}{\sum_i ACL_i} \qquad \forall i, j, k \qquad \text{(Eq. 7.9)}$$

Where PS, ACL and CMS correspond to Performance Score, Aspect Connection Level from Table 7-7, and Circularity Metric Scores from Table 7-5, respectively. And *i*, *j*, and *k* are defined as follows:

i: Major industry aspects defined (i= 1, 2, .. , 5)

j: Repair shipyards (j= A, B, C)

k: Circularity metrics utilised (k= RS-CM 1, RS-CM 2, …, RS-CM 9)

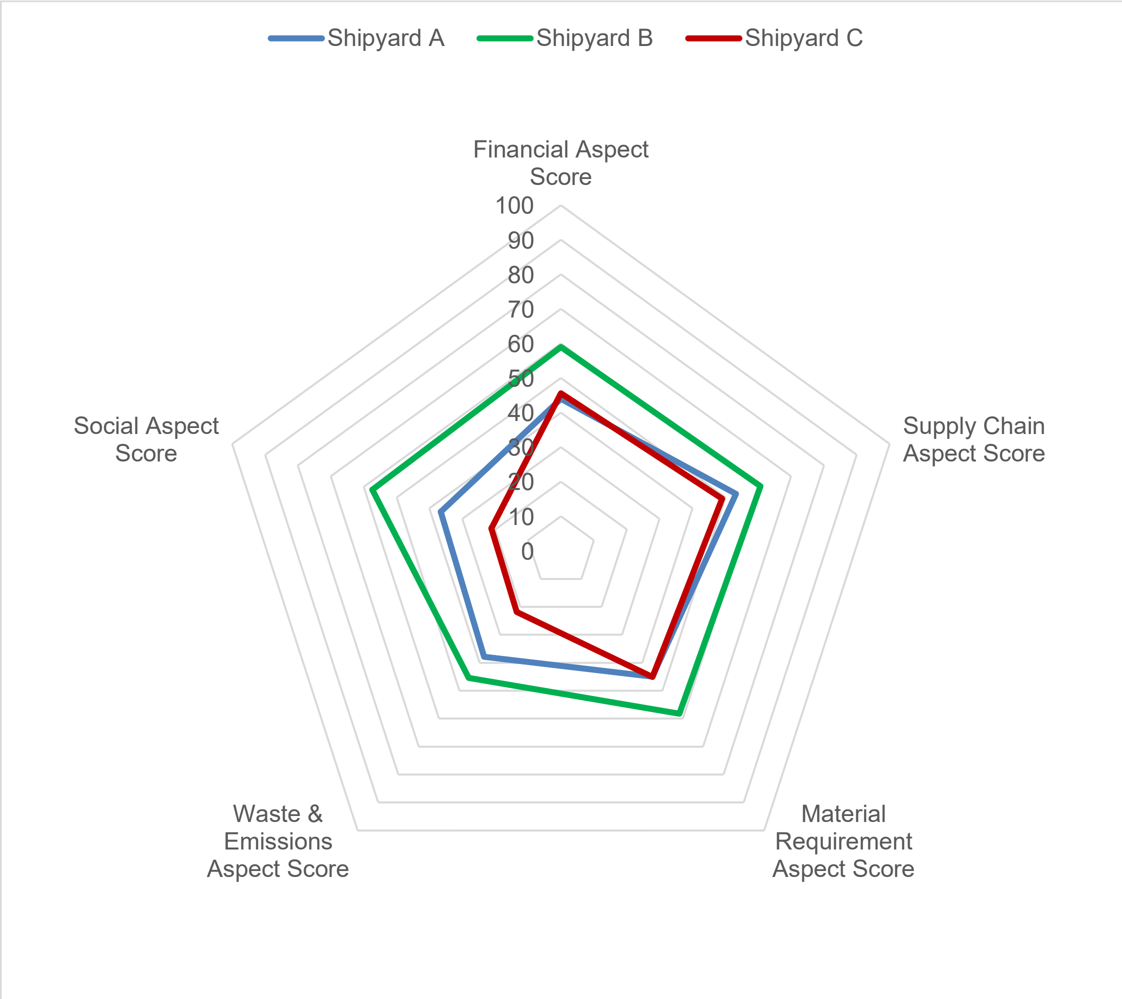


Figure 7-7: The performance of the shipyards according to major industry aspects.

The performance chart for the shipyards, presented in Figure 7-7, indicates a significant difference between all three. The areas of corresponding pentagons give an initial idea about the overall performance. Shipyard B is the best scoring facility amongst all three, while Shipyard A is the second, and Shipyard C is the lowest performing. To capture in-depth insights into each shipyard's specific strengths and weaknesses, a detailed analysis of their performance in each aspect is necessary. This analysis will thoroughly comprehend the implementation of circularity and areas for enhancement within each participating organisation.

In the financial aspect, Shipyard B leads with 59.0, while Shipyard C and A performed quite close, 45.6 and 44.0, respectively. As illustrated in Table 7-7, three CMs are strongly associated with this aspect, namely, circular revenue (RS-CM 6) and usage of reused parts in repair and maintenance (RS-CM 2 and 3). Also, the lead time metric (RS-CM 1) is also moderately linked to the financial aspect. While Shipyard A lags behind in most metrics, Shipyard C keeps up with Shipyard B in three of the most effective four: RS-CM 1, RS-CM 2, and RS-CM 6. Results indicate that Shipyard C has the potential for improvement in certain areas to surpass Shipyard B in overall performance. By focusing on strengthening circular revenue and utilising more reused parts in repair and maintenance, Shipyard C could potentially close the gap with Shipyard B even further. On the other hand, Shipyard A has more room for improvement across RS-CM 2, 3, and 6, indicating a need for a comprehensive strategy to enhance performance in adopting reused parts in their operations and reflect that in their sales. With targeted efforts and strategic investments such as providing options to their customers and enhancing marketing of circular products, Shipyard A can work towards closing the gap with its competitors and achieving a higher financial impact of circularity.

For the supply chain aspect, shipyards B, A, and C performed at 60.7, 53.2, and 49.0, respectively. The performance gap between the shipyards is relatively close in this aspect. The most effective CMs related to this aspect were found to be circular parts lead time (RS-CM 1), volume (RS-CM 4), and quality (RS-CM 5) of core parts returned to remanufacturer facilities. The difference mainly results from the performance difference in sending core parts and components back (volume) and the quality of the cores sent, which Shipyard A significantly lags behind the others. A reasonable approach for Shipyard A might be prioritising the reverse supply chain, forming new connections with remanufacturing facilities, and developing an execution plan to raise their volume of returns. This might cause a drop in their quality metric performance, but overall, it would boost their supply chain circularity score. Shipyards B and C, on the other hand, could consider prioritising their technical competencies in removing parts and components without damaging them to increase the quantity of sent-back items. This would also impact their inspection and quality control processes to boost the quality of returned parts.

The connection between circularity metrics and the material requirement is mainly based on reused part usage (RS-CM 2 and 3) and core part return metrics (RS-CM 4 and 5). In this aspect, Shipyard C and A nearly performed the same, 45.1 and 45.0, respectively, while Shipyard B scored the highest, 58.2. Any improvement mentioned in the paragraphs above regarding the circularity metrics will increase the circularity score from this perspective. Moreover, the circular revenue (RS-CM 6) and ratio of customers providing circular products (RS-CM 7) metrics are also moderately associated with this aspect. Given the limited resources of raw materials and ores on Earth, retaining materials in circulation for as long as possible is essential. This aspect is closely linked to contemporary environmental concerns beyond decarbonisation.

The performances in the waste and emissions aspects vary substantially between the three facilities. Shipyard B scored 45.4, followed by Shipyard A at 37.8, and Shipyard C at 21.8. The most effective circularity metrics on this aspect are identified as emission reduction due to circular practices (RS-CM 9) and hazardous waste ratio (RS-CM 8). In terms of emission reduction due to circular practices, all shipyards have improvement areas as there are losses in reverse supply chain and material requirement aspects. Especially the 23.6 point difference between Shipyards B and C indicates a huge but achievable improvement opportunity for the lower performing. Conversely, Shipyard A performed the best from the hazardous waste metric, while Shipyard C scored the lowest. Therefore, Shipyard A can serve as a benchmark for other shipyards to improve their hazardous waste management practices. By implementing strategies and revising waste handling processes to reduce hazardous waste, Shipyard C can work towards closing the gap with the top performer, thus enhancing their overall circularity metrics.

The social aspect is strongly associated with the ratio of customers who were provided circular parts and equipment (RS-CM 7) in Table 5, and metrics heavily impacting the waste and emissions aspect above are at the same time moderately impacting the social aspect. This could potentially reflect the impact of waste and emissions on the local community surrounding the shipyards and the workforce. Improving waste handling processes can benefit the environment and positively impact the social aspect by fostering a safer and healthier community for workers and residents. Furthermore, reaching more customers with circular products might increase awareness of circular practices and boost the maritime industry's public perception. That would help attract more investors and stakeholders who value sustainability and social responsibility, ultimately leading to a more competitive and successful industry.

While Shipyard B is the highest performer in all five dimensions, Shipyard A and Shipyard C performed similarly to each other in three out of five aspects: financial, supply chain, and material requirement. Certain circularity metrics in which Shipyard A performed even better than Shipyard B indicate that all shipyards can benefit from benchmarking and best practice sharing strategies to improve their sustainability performance in key areas. By doing so, they can become future-proof competitive in case of any regulatory changes or market shifts.

This case study demonstrates the difference between the circularity performance of three shipyards from the same region of the world. Benchmarking and transferring best practices within the industry yield positive results when preceded by thorough analysis and meticulous execution. Therefore, the results give an idea for each shipyard regarding their current circularity level, how well other shipyards in the region are doing, in which areas they are performing better or worse, etc. However, the main purpose of this section and showcasing a demonstration is to work up an appetite for the maritime stakeholders to adopt this approach and monitor their circularity levels regularly. Annual assessments would be strongly advised for stakeholders to build their own data, analyse the results of the actions they took during the year, compare the outcomes with previous years, see what works best for them as a company, or evaluate the impacts of an investment and eventually identify specific improvement areas for themselves.

Currently, there are no specific regulations or obligations concerning maritime circularity assessment. Nevertheless, this situation may evolve as the industry strives to achieve higher sustainability standards. When such practices are implemented, regulators or authorities may require the disclosure of certain circularity performance scores. This might even provide industry-wide best practice sharing and benchmarking opportunities. Furthermore, circularity performance has the potential to become a crucial component of corporate sustainability reports, which greatly influence public perception and the reputation of companies.

7.7 Chapter Summary

This chapter introduced nine sets of maritime stakeholder-specific circularity metrics, tailored to address the needs of nine key stakeholder groups in the maritime industry. The metrics were validated through stakeholder workshops, and a systematic approach to implementing and utilising these metrics in the real world was presented. A case study on three ship repair yards demonstrated the practical application of the metrics. By benchmarking the three participating shipyards, the study identified specific areas for improvement, highlighted best practices, and provided actionable insights to guide the facilities toward enhanced circularity. The findings emphasise the critical role of tailored metrics in enabling stakeholders to evaluate their performance systematically, align their operations with circular economy goals, and monitor progress over time. This chapter contributes a structured, data-driven approach to advancing circularity in the maritime industry, offering a replicable model for other stakeholder groups to adopt and implement.

8 Discussion

8.1 Chapter Overview

This section discusses the research carried out in this thesis. First, this chapter demonstrates how the research aims and objectives outlined in Section 3.3 have been achieved in Section 8.2. Next, the novelties and contributions to the literature in this PhD are discussed in Section 8.3. Then, Section 8.4 presents a comprehensive discussion of key outcomes. Finally, Section 8.5 discusses the path to impact.

8.2 Achievement of Research Aims and Objectives

This section presents how the research objectives defined in Section 3.3 are achieved. The objectives listed in Chapter 3 were described as follows:

- *To conduct a literature review on CE within the maritime industry and analyse circular practices across various transportation sectors for comparative insights.*

The detailed review in Chapter 2 achieved this objective by conducting a literature review on the aforementioned research topics. The reviewed topics commence with an overview of the broad CE concept, followed by an exploration of maritime circularity in Section 2.4, and a comparison with other transportation industries. Consequently, the gaps in the literature were identified and presented. The gaps included a lack of maritime-focused case studies, an absence of research on enablers for circular transition, and a need for circularity metrics tailored for maritime stakeholders.

- *To assess current circular practices, gain insights into the general situation in the maritime industry, and identify barriers hindering maritime circularity.*

Chapters 2 and 4 have succeeded in achieving this objective. In addition to the literature review in Chapter 2, Chapter 4 presented a comprehensive questionnaire designed within this PhD study to understand the general situation in the industry and discover barriers to the circular transition. The barriers are specified in Section 4.3.

- *To map high-value and high-potential onboard equipment, identifying opportunities for implementing circular economy practices to enhance their lifecycle value.*

This objective was achieved in Chapter 4, Section 4.4, which presented the top twelve high value and high potential onboard equipment. Since onboard engines are discovered to have the highest potential and value, advanced circular practices to close the loop for marine engines are also examined in this section.

- *To identify technology and strategy solutions that could be implemented to enhance circularity in the maritime industry, while examining current practices amongst well-known manufacturers in the industry.*

- *To conduct a case study on marine engine remanufacturing to demonstrate firsthand the advantages of advanced circular practices, followed by a comparative cost-benefit analysis with a new engine.*

Chapter 5 has accomplished the above two objectives by delving into technology and strategy solutions for a circular maritime industry, examining five mainstream marine engine manufacturers along with third-party remanufacturers, and carrying out a marine engine remanufacturing case study. In fact, Chapter 5 has highlighted four strategic, six technology, and three hardware solutions and examined maritime OEMs through those lenses. Furthermore, the case study has been linked to the solutions to stress their effectiveness.

- *To investigate the relationship between CE and digitalisation, with a focus on asset tracking systems like material passports to propose solutions for integrating digital advancements into the conventional merchant fleet lacking smart features.*

- *To create a customised database design to fill the existing gap in the merchant fleet, showcasing the system's advantages through a case study from the shipowners' perspective.*

Chapter 6 met the objectives listed above by exploring the relationship between digitalisation and circularity, researching material passport systems, and developing a maritime-specific database infrastructure to support the proposed maritime asset tracker system concept. Subsequent to the database validation procedures, a case study is conducted to illustrate the practical implementation of the system in a real-world context. This case study highlighted the potential benefits of implementing a digital material passport system in the maritime industry, showcasing its efficiency and effectiveness in improving sustainability practices within maritime operations.

- *To review existing CE indicators for other industries and develop tailored circularity metrics for the maritime industry to measure, monitor, and benchmark CE performances of key maritime stakeholder groups.*

Chapter 7 has succeeded in achieving the above objective. Section 7.3 reviewed existing CE metrics in detail, Section 7.4 proposed stakeholder-specific maritime circularity metrics, and Section 7.5 demonstrated how the proposed metrics can be utilised with a case study.

- *Overall, to establish a framework for implementing circular economy principles in the maritime industry, promoting sustainable practices and resource efficiency while enhancing economic growth and competitiveness.*

Consistent with the methodology of this thesis, Chapters 5, 6, and 7 establish a comprehensive framework for the maritime circular economy. The framework was introduced with a three-legged stool analogy in Section 3.5 in the methodology chapter. Then, Chapters 5, 6, and 7 each constituted a fundamental leg of this framework. Each chapter included its own specific case studies and stakeholder engagement events to reinforce the practical application of circular economy principles in the maritime industry. By examining real-world examples and engaging with stakeholders, this thesis provided a holistic approach to implementing sustainable circular practices in the sector. Thus, all objectives have been successfully accomplished.

8.3 Novelties and Contributions to the Knowledge

The thesis presents significant contributions to the field of CE in the maritime industry, with each chapter offering a unique advancement towards sustainable maritime practices. This research fills critical gaps in the literature and practical application of CE principles. As a result of this research, we now have a clearer understanding of how to systematically enable circular economy practices in the maritime industry through tailored strategies, digital infrastructure, and stakeholder-specific metrics. This integrated framework provides both theoretical insights and practical tools to drive the transition to circularity. The novelty of this work lies in its unique combination of theoretical advancements and practical implications, providing a structured pathway to guide maritime stakeholders through the transition to circularity.

The contributions of this research can be characterised as confirming, extending, or adding to existing knowledge, depending on the focus of each chapter. Chapter 5 confirms and extends existing knowledge, whereas Chapters 6 and 7 introduce entirely new dimensions to the field.

Chapter 5 contributes to the maritime industry's understanding of how to "close the loop" in operations, reduce waste, and enhance revenue streams by identifying suitable strategies and technology solutions tailored specifically to maritime stakeholders. This chapter confirms existing knowledge about the benefits of remanufacturing by empirically validating these benefits in the maritime context. It also extends knowledge by demonstrating how remanufacturing strategies can be operationalised within this sector. A detailed cost-benefit analysis demonstrates that remanufactured engines can be acquired at nearly half the cost of a new engine without sacrificing performance or operating efficiency. This chapter offers the first comprehensive study in maritime literature that addresses both strategy and technology solutions for circular practices, paired with a case study demonstrating the tangible benefits of remanufacturing. Indeed, the study's novelty lies in providing empirical evidence supporting circular end-of-life applications in maritime assets, which is largely absent in the existing literature. By building on prior research and extending its scope to maritime assets, this chapter provides a foundational step for maritime stakeholders, offering a practical example of how adopting CE principles—such as remanufacturing—can deliver economic and environmental benefits. The results of this study have significant implications for the industry's sustainability and could guide future developments in circularity-focused strategies.

Moreover, Chapter 6 focuses on a key obstacle to circularity in the maritime sector: the lack of digital infrastructure to support data collection, analysis, and sharing, which are crucial for implementing circular economy practices. This chapter adds new knowledge by proposing a novel, industry-wide database to serve as the digital backbone for maritime circularity. This research is the first of its kind to propose a robust, industry-wide database designed to facilitate the transition from linear to circular models in maritime operations. The novelty here lies in the database's ability to function as a digital backbone, enabling better coordination and communication across stakeholders, from shipowners to recycling facilities. Chapter 6 highlights the severe lack of digital tools currently available and the critical need to address this gap. The study advances the field by providing a framework for an industry-wide digital platform, laying the groundwork for future technological developments that could significantly enhance data availability and transparency, crucial for asset tracking and improving the circularity of the sector. Furthermore, this research contributes to the field by promoting the concept of a centralised digital infrastructure that could significantly transform the operational landscape of maritime circularity.

Furthermore, Chapter 7 significantly contributes to the field by addressing the need for circularity metrics tailored to maritime stakeholders. This chapter adds to the body of knowledge by proposing the first comprehensive set of CE indicators specifically designed for the maritime industry. This research marks the first time that CE indicators have been specifically reviewed and applied to the maritime industry, addressing a gap that has limited the industry's ability to measure progress in circularity effectively. Through a rigorous process that included a stakeholder engagement activity, a review of over 400 CE indicators, and workshops with industry professionals, this study developed a comprehensive set of metrics that cover all major life cycle stages in maritime operations. These metrics provide a structured approach to assessing stakeholder performance and are a significant addition to existing methodologies for CE evaluation.

The novelty of Chapter 7 lies in its thorough and systematic approach, ensuring that the developed metrics are both comprehensive and stakeholder specific. This study not only contributes to academic literature by filling a gap in CE measurement but also offers a practical tool for the maritime industry to evaluate and track its transition to circularity. By focusing on the maritime sector's unique needs, these metrics address a previously unexplored aspect of CE, offering actionable insights for both industry and policymakers. The metrics developed through this research offer a new level of insight and guidance for policymakers, businesses, and researchers, presenting a clear framework for measuring and advancing CE practices in a complex and dynamic industry.

Collectively, this PhD thesis presents a novel maritime circularity framework and provides invaluable insights into the advancement of circular practices within the maritime industry. By identifying key strategies and technology solutions, developing the first industry-wide digital platform for CE, and producing tailored circularity metrics, this thesis has made significant strides towards addressing the research gaps that hinder the maritime sector's transition to circularity. It confirms the theoretical benefits of circular economy principles, extends their application to the maritime sector, and adds entirely new tools and frameworks to facilitate this transition. These contributions are essential for future research, providing both theoretical and practical foundations for accelerating the adoption of circular economy principles across maritime operations.

8.4 General Discussion

The maritime industry, responsible for the majority of global trade, is at a critical stage where sustainable practices must be integrated into its operations. With the sector facing increasing environmental, regulatory, and economic pressures, transitioning towards a CE has become not just desirable but essential. The thesis can be divided into two main parts. The first part is the literature review and identifying barriers and opportunities of CE in the maritime industry (Chapters 2 and 4). The second part comprises Chapters 5, 6, and 7, each featuring an essential part of the maritime circularity framework developed. The framework showcases novel solutions and case studies that effectively demonstrate the feasibility and benefits of incorporating CE practices in the maritime industry, providing actionable insights.

During the barrier identification phase, a combination of inputs from the literature and stakeholder engagement events was gathered through surveys, workshops, and interviews, as depicted in Chapter 3. One of the challenges in collecting opinions and reasoning from diverse international participants, particularly from different stakeholder groups, is ensuring response consistency and excluding inconsistent responses from the analysis. This was addressed by carefully designing the survey questions as clear as possible, providing background information where necessary, and designing the survey in an interactive fashion (e.g., setting follow-up questions according to participant responses) and conducting rigorous data analysis to ensure the reliability and validity of the findings. In this way, the questionnaire presented in Chapter 4 was able to analyse 83 responses, which is considered a sufficient sample size for the research.

After carefully identifying the barriers along the way, the research presented in this thesis offers key insights into how this transition can occur. As the challenges necessitate a comprehensive, multi-stakeholder approach to implementing circular practices across the industry, this thesis proposed a distinctive maritime circularity framework to drive the necessary changes. By revealing the potential benefits of adopting circular economy principles in various case studies, this research aims to inspire action and drive momentum towards a more sustainable future for the global shipping industry.

Even though all the solutions developed in this thesis, one of the most challenging aspects for a successful transition to a circular maritime industry lies in the regulatory and policy framework. Currently, there is a lack of coherent global policies that incentivise the adoption of CE practices. Regulatory gaps exist, particularly regarding the use of second-hand or remanufactured parts, which are often treated with suspicion by both shipowners and regulatory bodies (Razmjooei et al., 2024). To overcome these barriers, policymakers must actively promote circularity through incentives such as tax breaks or subsidies for remanufactured items, as well as establish clearer guidelines that remove the stigma associated with using second-hand components. However, policymakers in the industry often hesitate to act unless compelled to do so; therefore, raising awareness and garnering support from key stakeholders are crucial to prompting policymakers to take action.

The thesis showcased the clear economic and environmental benefits of remanufacturing in the sector. Through a case study on high-speed marine engine remanufacturing, the research showed that the acquisition cost of a remanufactured engine can be nearly 50% lower than that of a new engine, without any compromise in performance or operating efficiency (Okumus et al., 2023c). This finding is significant as it provides a clear incentive for shipowners and operators to adopt remanufactured components, which could lead to substantial cost savings across the industry. On the other hand, the technical capabilities and testing equipment of the authorised dealer can be accounted for as a limitation for the case study in Chapter 5. Direct collaboration with an OEM's remanufacturing facility could have improved this limitation, but that was not possible for this case study because the OEM only performed remanufacturing in North America and would not welcome outside participants to their operations.

A maritime-specific database is created in Chapter 6 to enable maritime asset tracking. The database fills the lacking digital infrastructure gap and facilitates a dedicated material passport system. Considering the industry perception and low levels of awareness towards the CE, developing such solutions alone is not enough for effective adoption by the industry stakeholders. Therefore, showcasing the functionality and practical advantages is essential. The main difficulty in demonstrating the case study has been finding a volunteer ship owner/operator and real data to validate the effectiveness of the database in a real-world setting. After the case study was completed, another challenge was the impact estimation. The author opted to stay on the safe during the impact calculations to prevent overestimations. Therefore, the long-term impact estimates presented in Section 6.7.1 are actually modest figures from a strategic management point of view.

The development of a robust digital infrastructure that enables the maritime asset tracker (MAT) concept is one of the key contributions of this thesis. The proposed database solution, detailed in this research, offers a practical framework for overcoming these challenges by enabling better data collection, analysis, and sharing across the supply chain. By providing real-time access to information on the location, condition, and value of onboard components, this database would allow stakeholders to make more informed decisions about remanufacturing, reuse, and recycling opportunities. This digital backbone is particularly critical for older vessels, which are often underutilised or prematurely sent to scrapyards as scrap metal (UNCTAD, 2023). The database could help recover significant value from these ageing assets by identifying opportunities for refurbishment or reuse.

Moreover, this digital solution would provide a platform for ship recycling facilities to transform their business models. Currently, recycling yards focus primarily on the scrap value of vessels, overlooking the potential for recovering high-value components such as engines, pumps, or navigation systems (Gunbeyaz, 2019). By integrating the database into their operations, recyclers could shift their focus towards becoming suppliers of remanufacturable components, collaborating with OEMs to recover and reuse core parts. This would not only increase the financial value of end-of-life vessels but also reduce the environmental impact of ship recycling by minimising the waste of valuable materials.

The digital infrastructure developed in this thesis could also enable the establishment of regional hubs for circular practices, which could further enhance the adoption of CE principles in the maritime industry. Currently, end-of-life vessels are often sent thousands of miles from their operational origins to shipbreaking facilities, making it difficult to recover valuable components for reuse or remanufacturing. The database and MAT applications facilitate traceability of valuable onboard components throughout a vessel's life cycle, allowing stakeholders to track materials, engines, and other critical systems from installation to decommissioning. This level of traceability is particularly critical for two reasons. First, because it provides OEMs and third-party remanufacturers with the data needed to recover, refurbish, or remanufacture equipment (Okumus et al., 2023b). By enabling multiple stakeholders to interact with product information at different stages of a vessel's life, the MAT can substantially improve reverse supply chain operations and facilitate the recovery of high-value components from end-of-life vessels. And secondly, because such data will eventually pave the way for larger scale solutions such as circularity or remanufacturing hubs. For instance, cumulative data can be utilised to identify the optimum size and locations for such facilities to minimise costs of advanced circular practices. It can also be used to determine breakeven numbers of core collections, the number of components that need to be remanufactured from various product families, demand for circular products, and so on. Without such data, it is not possible to make such decisions objectively. However, if need to give some suggestions for the hubs, the author anticipates that the UK can become one of the hubs to combine the know-how in the remanufacturing operations with practical applications to create financial and social benefits. Other candidates can be Germany (due to manufacturing advancement), Turkey (due to having considerably high shipbuilding, repairing, and recycling capacities), and Indonesia (due to its excellent location in the middle of world trade routes). These hubs would not only facilitate the recovery of valuable materials but also create economic and social benefits in regions with existing maritime expertise and infrastructure.

Another significant contribution of this thesis is the development of tailored circularity metrics for the maritime industry, designed to assess and measure the progress of stakeholders in adopting CE practices in Chapter 7. The chapter proposes a total of 59 circularity metrics developed for nine maritime stakeholder groups and connects them with five major aspects, namely financial, supply chain, raw material requirement, waste and emissions, and social dimensions. After that, the chapter includes a case study on ship repair yards. In the case study, the circularity performances of three shipyards in the Mediterranean region were evaluated using the proposed set of metrics, and the results were used in benchmarking their respective performances, sharing potential best practices, and identifying the improvement areas for each facility. However, an important factor to mention here is that, ideally, the circularity performance of a business or organisation should be monitored regularly (advised annually), and the results should be used to make comparisons with the organisation's previous years' performances. The organisations should have their medium- and long-term strategic targets and keep track of their progress towards achieving those targets. By doing so, they might benefit from capturing reflections of any organisational change or managerial decisions on their circularity performance. This approach will facilitate ongoing improvement and alignment with circularity and sustainability goals. The approach to metrics makes it easier to compare stakeholder performance with industry standards, helping organisations establish achievable goals, monitor progress, and share best practices. The validation of the study through stakeholder engagement and real-world case studies demonstrates the practicality of the metrics, making sure that they are relevant and actionable. By offering clear guidelines and measurement tools, the study empowers professionals and researchers in the field to make informed decisions based on data, encourage innovation, and implement CE strategies that can result in cost savings, compliance with environmental regulations, and a reduced environmental impact of maritime operations

Moreover, the metrics provide a practical framework for tracking performance across various life cycle stages, from ship design and construction to operation and decommissioning. However, it is important to acknowledge that implementing these metrics will require substantial data collection efforts. While this research provides a robust framework for circularity metrics, data availability remains limited, particularly for forward-thinking metrics related to GHG emissions reduction and resource efficiency. In other words, the development of innovative metrics could precede the widespread availability of data necessary for their application. The absence of readily available data for forward-thinking metrics emphasises the innovative nature of this research and underscores the urgent need for systematic data collection efforts in the maritime industry.

Apart from tackling the industry's technical challenges, this research underscores the broader impact of circular economy practices in attaining the SDGs, specifically focusing on SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). The digitalisation of maritime materials and components through the MAT system also supports transparency and accountability, key components for advancing the global sustainability agenda. Therefore, the adoption of CE practices in the maritime industry can be viewed as a crucial facilitator of sustainability, guiding the industry towards more responsible resource utilisation and aiding global initiatives in combating climate change.

Finally, the success of the CE in the maritime industry will depend on stakeholders' willingness to embrace new ways of thinking and operating. This research has shown that while there is growing awareness of the importance of CE practices, significant cultural and organisational barriers remain. The industry needs to foster collaboration and transparency, where stakeholders share information and best practices to achieve common sustainability goals (Okumus et al., 2023b). By aligning incentives and promoting knowledge-sharing initiatives, the industry can overcome traditional barriers that prevent progress towards circularity.

The findings of this thesis lay a solid foundation for future research and policy development in the maritime sector. By addressing the current gaps in digital infrastructure, stakeholder coordination, and regulatory support, the maritime industry can move towards a more sustainable future. The tools and strategies outlined in this research provide a comprehensive framework and roadmap for accelerating the adoption of CE practices, ensuring that the maritime sector not only achieves global sustainability targets but also thrives in a circular, resource-efficient economy.

8.5 Path to Impact

This PhD research has demonstrated potential significant economic and environmental impact opportunities in the maritime industry by developing and demonstrating practical CE solutions. The case studies, stakeholder engagements, and tailored framework presented in this thesis highlight the immediate and long-term benefits of adopting circularity in the sector.

8.5.1 Demonstrated Impacts

The research findings, particularly the case study on marine engine remanufacturing in Chapter 5, demonstrate clear economic and environmental benefits. The remanufactured engine delivered equal performance compared to a new one, with an acquisition cost of nearly half of a new engine (48.3% financial savings as calculated). Additionally, the case study provided top-level reliability and reassurance by providing longer warranty coverage than new engines. The remanufactured unit has been working for around two years and has not experienced any significant breakdowns or performance issues. This showcases the durability and quality of remanufactured engines in the marine sector, further emphasising the benefits of adopting circularity practices.

In Chapter 6, the maritime-specific database and the MAT concept showed significant potential for improving asset tracking and management. The case study demonstrated an 83% increase in the end-of-life value of a remanufactured vessel, emphasising the financial benefits of implementing a structured asset tracking system. This translates into an estimated impact of $818 million USD for just 1% of the global fleet, $14.5 billion USD for the European fleet, and a potential $27 billion USD benefit if applied to one-third of the world fleet.

Furthermore, Chapter 7 introduced tailored circularity metrics to enhance performance evaluation for diverse stakeholder groups in the maritime sector. The case study on ship repair yards provided valuable feedback, highlighting improvement areas and showcasing the metrics' practical application. This research sets the stage for systematic, data-driven tracking of circularity performance across the industry, enhancing transparency and driving continuous improvement.

8.5.2 Potential Future Impacts

Demonstrated impacts mainly focus on the economic dimension; however, further research could explore the social and environmental impacts of the circular transition in the maritime sector. The transition to a circular economy in the maritime sector has the potential to generate substantial future impacts, particularly in the context of developed countries’ reliance on external raw materials. Similar to many other heavy industries, numerous marine OEMs are located in developed countries, such as those in the EU, where advanced equipment is manufactured using high technology manufacturing methods. However, those countries usually depend on external resources for essential raw materials such as aluminium, cobalt, copper, iron, and lithium (Eurostat, 2023b). By transitioning to CE practices, the dependence on imported raw materials can be significantly reduced.

For instance, developed countries can reduce their reliance on raw material imports by keeping valuable materials in circulation through remanufacturing, reuse, and recycling. This transition would not only alleviate economic pressures related to resource scarcity but also enhance the self-sufficiency of developed countries in terms of material supply. In 2022, the EU's self-sufficiency rates for critical materials remained relatively low—11% for aluminium, 19% for cobalt, 19% for lithium, and 23% for iron—indicating a significant opportunity for improvement (Eurostat, 2023b). By integrating advanced circular practices in their manufacturing sectors, the European countries might increase these rates and contribute to the overall raw material supply within the EU.

Furthermore, the contribution of recycled materials to raw material demand is also an area where CE practices can have a major impact. For example, the recycling rates for key materials like aluminium (32%), iron (31%), and cobalt (22%), are still far below their potential (Eurostat, 2023a). A comprehensive shift to a circular consumption model could substantially increase these recycling rates, thereby reducing the need for raw material extraction from external sources, which amounted to 2.5 billion metric tonnes to meet the EU's consumption needs in 2022 (Eurostat, 2024).

Regarding material retention in the CE, Zhang et al. (2021) concluded that advanced circular practices could significantly extend the theoretical lifetime of critical components like engines. Their findings indicate a potential increase from 18 years to over 40 years for automotive engines through remanufacturing processes. Applying similar principles in the maritime sector might extend the life cycles of critical components such as engines, pumps, and other valuable equipment. Thus, keeping valuable metals like steel, nickel, and chromium in circulation for much longer. This shift would have far-reaching impacts on the industry's raw material consumption, waste generation, and overall sustainability. By reducing the demand for virgin raw materials, the maritime sector can contribute significantly to global efforts in resource conservation.

In conclusion, the results of this thesis demonstrate both proven impacts and estimated potential impacts of circular practices. By developing a structured maritime circularity framework, showcasing the real-world benefits of circularity, and outlining potential future impacts, this research provides a roadmap for accelerating the industry's transition to sustainability. The findings presented here serve as a valuable resource for industry stakeholders, policymakers, and researchers, enabling informed decisions that can drive significant environmental and economic progress in the maritime sector.

8.6 Chapter Summary

This chapter summarised the achieved research aims and objectives, briefly discussing the limitations, assumptions, and difficulties encountered during the PhD study. Novelties and contributions were also clearly presented.

9 Conclusions and Recommendations

9.1 Chapter Overview

The conclusions of the research conducted during this PhD are summarised in this chapter, and recommendations for future research will be provided as a continuation of the work presented in the main chapters of this thesis.

9.2 Conclusions

The research conducted in this PhD thesis focused on facilitating the maritime industry's circularity transition and increasing value extraction from end-of-life assets. The CE concept has gained significant traction in academia since 2013; however, maritime circularity has been overlooked and barely mentioned until the 2020s. This gives rise to considerable research gaps, particularly in adopting advanced circular practices tailored to maritime assets and stakeholders. To the best of the author's knowledge, there is no framework developed to address the barriers to the maritime industry's circularity. In fact, even the barrier identification is very limited in existing literature, with a lack of practical solutions proposed. Therefore, the objectives of this study began with assessing current practices, gaining insights regarding the overall situation, identifying the barriers and opportunities in the industry, and then delving into solutions and conducting case studies.

Stakeholder engagement events organised, and literature reviews conducted within this study have portrayed the significant barriers to maritime circularity in Chapter 4. The significant barriers identified included low awareness levels of stakeholders regarding the CE concept, lack of a functioning reverse supply chain or infrastructure, and a negative perception with limited industry acceptance towards circular products. A comprehensive questionnaire presented in this section revealed that 25% of the participants had never heard of the CE concept before the survey. Additionally, only 45% of the remaining participants feel confident in the maritime's circular transition. On the other hand, opportunities lie in moving towards advanced circular practices such as remanufacturing rather than the current basic metal recycling processes. Such a transition will provide considerable benefits in all sustainability dimensions. Valuable and high potential onboard components include but are not limited to main and auxiliary engines, hydraulic pumps and motors, emergency generators, purifiers, compressors, and cranes. The questionnaire revealed that warranty coverage, price advantage, and aftersales service support factors make remanufactured products preferable in the industry. 89.5% of the respondents, who were initially against reused or remanufactured products, stated that they would prefer such circular products if they were guaranteed the same reliability and quality as a newly manufactured product. Given that engines have been found to have the highest value and highest remanufacturing potential, both in the questionnaire and in the literature, this research particularly focused on marine engines in the following sections. The remanufacturing or reusing capabilities of engines and hydraulic components mainly come from the OEMs, as 86% of them declared they are able to remanufacture, while 81.8% stated that they are willing to begin or intensify their reuse, remanufacture, or repurposing operations. Finally, the majority of the participants (71%) expressed that future CE opportunities in the maritime industry lie with advanced restorative practices such as remanufacturing. They particularly highlighted the need to carry out case studies showcasing the benefits of such circular practices.

Chapters 5, 6, and 7 constitute the maritime circularity framework developed in this thesis. Like a three-legged stool, these sections each carry essential parts of the framework. Chapter 5 is concerned with identifying solutions and showcasing financial benefits of advanced circular practices; Chapter 6 delves into digital infrastructure for asset tracking features and bringing transparency to the industry; and Chapter 7 aims for industrywide alignment and circularity performance monitoring tools tailored for different stakeholder groups.

Chapter 5 presented strategic and technological solutions that might support the circular transition for the maritime industry. The strategic solutions included closed-loop supply chain approaches, seeding strategies, component take-back strategies, and PSS solutions. Technology solutions included I4.0 applications, IoT, big data analytics, database solutions, digital twins, and SRDM, along with complementary hardware such as smart sensors, RFID, and QR codes. Best practices of the leading marine engine OEMs such as Wartsila, Caterpillar, Volvo Penta, mtu, and Cummins were also investigated in this chapter, and the findings indicated they acquired some of the solutions presented in this chapter to certain degrees. Furthermore, an overall marine engine remanufacturing process is revealed based on the literature and OEM practices examined in this thesis. A five-phase remanufacturing process clearly demonstrated the remanufacturing steps. Following that, a case study is carried out to showcase the remanufacturing operation and compare the remanufactured product with a brand-new alternative. A high-speed passenger ferry's main engine was remanufactured for that purpose, and it was tested in an engine testing facility to document its performance. The results showed the same performance with a brand-new engine, and cost-benefit analysis clearly showed 48.3% financial savings compared to the brand-new alternative. Instead of a 2-year standard warranty, the OEM has provided better coverage (3 years longer) for the remanufactured engine to highlight that they support such circular practices.

In chapter 6, on top of the questionnaire mentioned in Chapter 4, a series of semi-structured interviews and workshops were carried out to capture maritime stakeholder needs. One of the significant gaps identified is the lack of an asset tracking system in maritime. Therefore, end-of-life vessels and onboard equipment were not being properly monitored and managed, leading to inefficiencies in the reverse supply chain, especially for the older vessels, which do not have smart onboard equipment. To bridge that gap, this study has delved into the CE and digitalisation literature and investigated existing material passport concepts. Eventually a maritime asset tracking system was proposed, and a database infrastructure to facilitate the tracking and management of end-of-life vessels was created in this thesis. The stakeholder roles and responsibilities were defined, and database interface forms and example queries were presented in Chapter 6. Moreover, a dedicated database validation workshop was organised with 12 experts from the industry, and the database has been revised according to their feedback. Finally, a case study has been carried out to demonstrate the potential benefit of the developed asset tracking system for an example vessel, which resulted in an 83% increase in the end-of-life value of the case study vessel. In the last step, the overall impact of such a system was calculated as 818 million USD for 1% of the world fleet, while the total European fleet's impact is 14.5 billion USD, and one-third of the world fleet's impact is estimated around 27 billion USD.

Chapter 7 investigated existing circularity metrics in the literature, screened, and analysed them to eventually develop a set of circularity indicators specific to the maritime stakeholders. A maritime-focused circularity assessment that proposed 59 metrics in total for 9 different stakeholder groups, including ship designers, shipyards, classification societies, and so forth, came after a thorough review of the current CE metrics. Following that, validation workshops were organised for each stakeholder group to confirm and refine the proposed metrics and increase their relevance and effectiveness in addressing the needs and challenges of the maritime stakeholders. A total of 27 professionals participated in these workshops, providing valuable feedback and insights. This research also associated the circularity metrics with five major aspects, namely financial, supply chain, raw material consumption, waste and emissions, and social aspects. Furthermore, a case study on ship repair yards was presented to show how the developed metrics can be practically used. Three shipyards participated in the case study for this purpose. According to the step-by-step guidance provided in this chapter, their respective circularity performances were evaluated and compared, highlighting areas for improvement and best practices. The case study demonstrated the practical application of the circularity metrics in a real-world setting, showcasing how circularity assessment can be standardised and monitored, and provided individual feedback for participating shipyards.

Overall, this thesis contributes to the advancement of circular economy principles in the maritime industry by providing a structured maritime circularity framework, offering valuable insights for its stakeholders, and showcasing real-world benefits of a circular maritime industry. The results of this thesis provide a foundation for the future and can serve as a valuable resource for stakeholders looking to implement circular economy practices in the maritime industry. Additionally, the findings can inform policymakers and industry leaders on the potential economic and environmental benefits of transitioning towards a more circular maritime industry.

9.3 Recommendations for Future Research

This section presents the author's recommendations for potential future research:

- Economic benefits are significant motivators towards remanufactured products in the maritime industry. Chapter 5 explored end-of-life solutions and showcased the advantages of advanced restorative practices using a case study on marine engines. Conducting more case studies on remanufacturing and refitting different equipment (e.g., medium- or low speed engines, hydraulic pumps and motors, purifiers, etc.) on existing and new ships would greatly benefit the industry and literature.
- The database from Chapter 6 can be combined with a value estimation module to assess onboard equipment during surveys. Machine learning algorithms can enhance the module's capabilities to estimate the value of onboard equipment prior to reaching the end-of-life stage. This might allow for accurately estimating the vessel's end-of-life value and finding the optimum end-of-life solutions for onboard components.
- Further implementation and testing of the database in additional case studies should involve collaboration with stakeholders like shipyards, ship owners, recycling facilities, and OEMs. Furthermore, the MAT concept can be expanded to incorporate end-of-life routes based on product conditions for each piece of equipment, aiming to enhance circularity.
- It is important to note that the innovative circularity metrics in Chapter 7, especially those like OEM-CM 6 or RF-CM 3 (GHG emission reduction related indicators), often precede the widespread availability of data necessary for their application. The absence of readily available data for some of these forward-thinking metrics highlights the cutting-edge nature of this research and points to an urgent need for systematic data collection efforts within the maritime industry. This gap provides a chance for future research to expand on

this groundwork, underscoring the importance of data-driven approaches to validate and enhance these metrics.

- One limitation of the study in Chapter 7 is the limited number of facilities included in the case study section. Future research should expand on this by examining a broader range of stakeholder groups, such as shipowners, operator companies, ship recycling facilities, and shipbuilding yards, to gain a more comprehensive understanding of the industry's progress toward sustainability. In addition, including stakeholders from other regions, such as newbuilding yards from China, South Korea, and the EU, will help establish global benchmarks. Although the metric development and initial case study offered valuable insights, conducting additional testing in varied stakeholder environments and implementing a comprehensive data collection campaign can further validate and refine the metrics, ultimately providing a more defined circularity roadmap for the maritime sector.
- Moreover, exploring the initial investment needed to improve an organisation's circularity performance and demonstrating long-term cost savings through circular practices to address financial concerns could be a significant focus for future research. This would help address financial concerns and provide a clearer business case for adopting circular economy strategies for maritime stakeholders.
- Finally, maritime circularity metrics can form a foundation for the industry's regulatory bodies and global authorities. Currently, circular products are in a grey area where certification issues and regulations limit their adoption. This can be overcome with a well-structured approach and even further boosted with an incentivisation mechanism based on monitored circularity performance. Moreover, future research can focus on potential policy recommendations to support the implementation of circular economy practices in the maritime industry. These policies could include setting limits on new raw material use, implementing environmental taxes, promoting product-as-a-service models that decouple consumption from resource use, and assisting global policymakers such as IMO in rewarding circular practices and encouraging

widespread adoption of environmentally friendly initiatives within the industry.

References

Abbey, J., Geismar, H., & Souza, G. (2018). Improving Remanufacturing Core Recovery and Profitability Through Seeding. *Production and Operations Management*, *28*. https://doi.org/10.1111/poms.12937

Abbey, J. D., & Guide, V. D. R. (2018). A typology of remanufacturing in closed-loop supply chains. *International Journal of Production Research*, *56*(1-2), 374-384. https://doi.org/10.1080/00207543.2017.1384078

Acerbi, F., & Taisch, M. (2020). A literature review on circular economy adoption in the manufacturing sector. *Journal of Cleaner Production*, *273*, 123086. https://doi.org/10.1016/j.jclepro.2020.123086

AFRA. (2022). *About Us*. Retrieved January from https://afraassociation.org

Afrinaldi, F., Liu, Z., Taufik, Zhang, H.-C., & Hasan, A. (2017). The Advantages of Remanufacturing from the Perspective of Eco-efficiency Analysis: A Case Study. *Procedia CIRP*, *61*, 223-228. https://doi.org/10.1016/j.procir.2016.11.161

Agarwala, N. (2023). Promoting Circular Economy in the shipping industry. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, *7*(4), 2276984. https://doi.org/10.1080/25725084.2023.2276984

Ahasan, S., Zaman, F. N., & Ahmed, T. (2021). *Perspective of Circular Economy in Bangladesh: A Comprehensive Review Towards Ship Demolition Industry* 4th European International Conference on Industrial Engineering and Operations Management, Rome. https://www.scopus.com/record/display.uri?eid=2-s2.0-85126232358&origin=inward&txGid=dc884b815904ec9412f3475ce0c1a449

Airbus, S. (2008). Process for advanced management of end-of-life of aircraft (PAMELA). *Airbus Academy: Champniers, France*.

Akano, D. I., Ijomah, W., & Windmill, J. (2021). Stakeholder considerations in remanufacturability decision-making: Findings from a systematic literature review. *Journal of Cleaner Production*, *298*, 126709. https://doi.org/10.1016/j.jclepro.2021.126709

Akçali, E., & Morse, M. A. (2004). Seeding strategies in remanufacturing. IIE Annual Conference. Proceedings,

Akturk, M. S., Abbey, J. D., & Geismar, H. N. (2017). Strategic design of multiple lifecycle products for remanufacturing operations. *IISE Transactions*, *49*(10), 967-979. https://doi.org/10.1080/24725854.2017.1336684

Alcott, B. (2005). Jevons' paradox. *Ecological Economics*, *54*(1), 9-21. https://doi.org/10.1016/j.ecolecon.2005.03.020

Aleksić, A., Rađenović, T., & Simonović, Z. (2022). Resource management and performance measurement indicators in the circular economy. *Economics of Sustainable Development*, *6*(2), 31-42. https://doi.org/10.5937/ESD2202031A

Alqahtani, A. Y., Gupta, S. M., & Nakashima, K. (2019). Warranty and maintenance analysis of sensor embedded products using internet of things in industry 4.0. *International Journal of Production Economics*, *208*, 483-499. https://doi.org/10.1016/j.ijpe.2018.12.022

APRA. (2021). *APRA (Automotive Parts Remanufacturers Association)*. Retrieved DECEMBER 20 from https://apraeurope.org/about-us/

Archer, M., Bhaskar, R., Collier, A., Lawson, T., & Norrie, A. (2013). *Critical realism: Essential readings*. Routledge.

ASTM. (2017). *ASTM A572/A572M-12, Standard specification for high-strength low-alloy columbium-vanadium structural steel*. American Society for Testing and Materials (ASTM). https://www.astm.org/a0572_a0572m-12.html

ASTM. (2019). *ASTM A131/A131M-19, Standard Specification for Structural Steel for Ships*. American Society for Testing and Materials (ASTM). https://www.astm.org/a0131_a0131m-19.html

Bititci, U., Turner, T., Mackay, D., Kearney, D., Parung, J., & Walters, D. (2007). Managing synergy in collaborative enterprises. *Production Planning & Control*, *18*(6), 454-465. https://doi.org/10.1080/09537280701494990

Bjerkan, K. Y., & Seter, H. (2019). Reviewing tools and technologies for sustainable ports: Does research enable decision making in ports? *Transportation Research Part D: Transport and Environment*, *72*, 243-260. https://doi.org/10.1016/j.trd.2019.05.003

Bletsas, O., Gunbeyaz, S. A., Kurt, R. E., & McKenna, S. A. (2017). *"Identification and Valuation Of Equipment and Materials For Reuse, Remanufacturing, and Recycling On Marine Assets" Final Report*. https://pureportal.strath.ac.uk/en/projects/identification-and-valuation-of-equipment-and-materials-for-reuse

Blomsma, F., & Tennant, M. (2020). Circular economy: Preserving materials or products? Introducing the Resource States framework. *Resources, Conservation and Recycling*, *156*, 104698. https://doi.org/10.1016/j.resconrec.2020.104698

Boukhatmi, Ä., Nyffenegger, R., & Grösser, S. N. (2023). Designing a digital platform to foster data-enhanced circular practices in the European solar industry. *Journal of Cleaner Production*, *418*, 137992. https://doi.org/10.1016/j.jclepro.2023.137992

Boulding, K. E. (1966). The economics of the coming spaceship earth. In *Environmental quality in a growing economy* (pp. 3-14). Resources for the Future Forum,. http://arachnid.biosci.utexas.edu/courses/thoc/readings/boulding_spaceshipearth.pdf

Bracquené, E., Dewulf, W., & Duflou, J. R. (2020). Measuring the performance of more circular complex product supply chains. *Resources, Conservation and Recycling*, *154*, 104608. https://doi.org/10.1016/j.resconrec.2019.104608

Brent, A. C., & Steinhilper, R. (2004). Opportunities for remanufactured electronic products from developing countries: Hypotheses to characterise the perspectives of a global remanufacturing industry. 2004 IEEE Africon. 7th Africon Conference in Africa (IEEE Cat. No. 04CH37590),

Bressanelli, G., Perona, M., & Saccani, N. (2017). Reshaping the Washing Machine Industry through Circular Economy and Product-Service System Business Models. *Procedia CIRP*, *64*, 43-48. https://doi.org/10.1016/j.procir.2017.03.065

Calzolari, T., Genovese, A., & Brint, A. (2022). Circular Economy indicators for supply chains: A systematic literature review. *Environmental and*

Sustainability Indicators, *13*, 100160. https://doi.org/10.1016/j.indic.2021.100160

Caterpillar. (2013). *Cat Reman Business Model*. https://www.youtube.com/watch?v=k1oyoipNnXw

Caterpillar. (2021). *Caterpillar's Circular Economy*. Retrieved 13/12/2021 from https://www.caterpillar.com/en/company/sustainability/remanufacturing.html

Caterpillar. (2022). *Cat Reman Parts, Components and Diesel Engines*. Retrieved 24/02/2022 from https://www.cat.com/en_US/products/new/parts/reman.html

Caterpillar. (2023). *2022 Sustainability Report* [Annual report]. https://www.caterpillar.com/en/company/sustainability/sustainability-report.html

Caterpillar. (2024). *2023 Sustainability Report*. https://www.caterpillar.com/en/company/sustainability/sustainability-report/download-sustainability-report.html

Caterpillar. (n.d.-a). *The Benefits of Remanufacturing*. Retrieved 08/04/2024 from https://www.caterpillar.com/en/company/sustainability/remanufacturing/benefits.html

Caterpillar. (n.d.-b). *Caterpillar's Remanufacturing Process*. Retrieved 25/02/2022 from https://www.caterpillar.com/en/company/sustainability/remanufacturing/process.html

Caterpillar. (n.d.-c). *Caterpillar. Why Condition Monitoring?*. Retrieved 19/11/2021 from https://www.cat.com/en_US/support/maintenance/fleet-management/condition-monitoring.html

Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular Digital Built Environment: An Emerging Framework. *Sustainability*, *13*(11), 6348. https://doi.org/https://doi.org/10.3390/su13116348

Chen, D. Q., Preston, D. S., & Swink, M. (2015). How the Use of Big Data Analytics Affects Value Creation in Supply Chain Management. *Journal of Management Information Systems*, *32*(4), 4-39. https://doi.org/10.1080/07421222.2015.1138364

Chen, Z., & Huang, L. (2021). Digital twins for information-sharing in remanufacturing supply chain: A review. *Energy*, *220*, 119712. https://doi.org/10.1016/j.energy.2020.119712

Chernyshov, E. A., Romanov, A. D., & Romanova, E. A. (2016). High-Strength Shipbuilding Steels and Alloys. *Metallurgist*, *60*(1), 186-190. https://doi.org/10.1007/s11015-016-0271-1

Chesbrough, H., Lettl, C., & Ritter, T. (2018). Value Creation and Value Capture in Open Innovation. *Journal of Product Innovation Management*, *35*(6), 930-938. https://doi.org/10.1111/jpim.12471

Chierici, E., & Copani, G. (2016). Remanufacturing with Upgrade PSS for New Sustainable Business Models. *Procedia CIRP*, *47*, 531-536. https://doi.org/10.1016/j.procir.2016.03.055

Circle Economy. (2024). *European remanufacturing industry estimated at €30bn with potential to triple by 2030*. Circle Economy,. Retrieved 17/06/2024 from https://www.circle-economy.com/news/european-remanufacturing-industry-estimated-at-eu30bn-with-potential-to-triple-by-2030

Ciulli, F., Kolk, A., & Boe-Lillegraven, S. (2020). Circularity Brokers: Digital Platform Organizations and Waste Recovery in Food Supply Chains. *Journal of Business Ethics*, *167*(2), 299-331. https://doi.org/10.1007/s10551-019-04160-5

Clarksons. (2022). *Shipping Intelligence Network* https://sin.clarksons.net/

ClassNK. (2023). *Ship Recycling Convention (the Hong Kong Convention)*. Retrieved 14/13/2023 from https://www.classnk.or.jp/hp/en/activities/statutory/shiprecycle/index.html

Copani, G., & Behnam, S. (2020). Remanufacturing with upgrade PSS for new sustainable business models. *CIRP Journal of Manufacturing Science and Technology*, *29*, 245-256. https://doi.org/10.1016/j.cirpj.2018.10.005

CRR. (n.d.). *Centre for Remanufacturing & Reuse (CRR)*. Centre for Remanufacturing & Reuse,. Retrieved 17/06/2024 from https://www.remanufacturing.org.uk/

Cummins. (2021). *Cummins Celebrates Global Remanufacturing Operations*. Retrieved 09/01/2022 from https://www.cummins.com/news/2021/04/08/cummins-celebrates-global-remanufacturing-operations

Cummins. (n.d.-a). *Aftermarket & remanufacturing*. Retrieved 09/01/2022 from https://www.cummins.com/components/electronics-fuel-systems/aftermarket-reman

Cummins. (n.d.-b). *Recon Marine Engines*. Retrieved 2022 from https://www.cummins.com/engines/recon-marine

DAC. (2019). *D1.5 - Aerospace Value Chain map in a Circular Economy Perspective* (D1.5). (Development of a Joint Cluster Partnership Strategy, Issue. Distretto Aerospaziale della Campania (DAC). https://www.eacp-aero.eu/fileadmin/user_upload/EACP/news/pdf/D1.5_EUROSME.pdf

Dasgupta, S. (2019). *What is Karadeniz Powership?* Retrieved 06/06/2024 from https://www.marineinsight.com/types-of-ships/what-is-karadeniz-powership/

de Oliveira, C. T., Dantas, T. E. T., & Soares, S. R. (2021). Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. *Sustainable Production and Consumption*, *26*, 455-468. https://doi.org/10.1016/j.spc.2020.11.024

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., & Ioppolo, G. (2021). A systematic review for measuring circular economy: The 61 indicators. *Journal of Cleaner Production*, *281*, 124942. https://doi.org/10.1016/j.jclepro.2020.124942

Desing, H., Braun, G., & Hischier, R. (2020). Ecological resource availability: a method to estimate resource budgets for a sustainable economy. *Global Sustainability*, *3*, e31, Article e31. https://doi.org/10.1017/sus.2020.26

Devaux, C., & Nicolaï, J.-P. (2020). Designing an EU Ship Recycling Licence: A Roadmap. *Marine Policy*, *117*, 103826. https://doi.org/10.1016/j.marpol.2020.103826

Di Maio, F., & Rem, P. C. (2015). A robust indicator for promoting circular economy through recycling. *Journal of Environmental Protection*, *6*(10), 1095. https://doi.org/10.4236/jep.2015.610096

Di Maio, F., Rem, P. C., Baldé, K., & Polder, M. (2017). Measuring resource efficiency and circular economy: A market value approach. *Resources,* *Conservation and Recycling*, *122*, 163-171. https://doi.org/10.1016/j.resconrec.2017.02.009

Directive, E. (2000). 53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles. *Official Journal of the European Union, L Series*, *21*, 34-42.

DIVEST. (2011). *D4.3 Ship Full Life Cycle Map*. S. F. P. EUROPEAN COMMISSION, CALL IDENTIFIER: FP7-SST-2007-RTD-1.

DNV. (2023). *IHM Part I Certification*. Retrieved 13/12/2023 from https://www.dnv.com/maritime/insights/topics/ihm-ship-recycling/ihm-part-1-certification.html

EC Directive. (2008). 98/EC of the European Parliament and of the Council, on waste and repealing certain Directives. *Official Journal of the European Union*(312), 3-30.

EC, E. C. (2016). *The EU Ship Recycling Regulation*. Retrieved 5 September from http://ec.europa.eu/environment/waste/ships/

ECB, E. C. B. (2022). *Key ECB interest rates*. ECB, European Central Bank. Retrieved 11/09/2022 from https://www.ecb.europa.eu/stats/policy_and_exchange_rates/key_ecb_interest_rates/html/index.en.html

Ellen MacArthur Foundation. (2019). *The butterfly diagram: visualising the circular economy*. Ellen MacArthur Foundation. Retrieved 03/02/2024 from https://www.ellenmacarthurfoundation.org/circular-economy-diagram

Ellen MacArthur Foundation. (2021). *Design and business model considerations for heavy machinery remanufacturing: Caterpillar*. Ellen Macarthur Foundation,. Retrieved 16/10/2023 from https://www.ellenmacarthurfoundation.org/circular-examples/design-and-business-model-considerations-for-heavy-machinery-remanufacturing

Ellen MacArthur Foundation. (2022). *Circulytics Indicator List* (Circulytics, Issue. Circulytics & Ellen MacArthur Foundation. https://emf.thirdlight.com/link/1pzbxosbi6hl-ei3tq6/@/preview/3

Ellen MacArthur Foundation, & Granta Design. (2015). *Towards a circular economy: Business rationale for an accelerated transition.* Ellen MacArthur Foundation.

https://emf.thirdlight.com/file/24/_A-BkCs_h7gfln_Am1g_JKe2t9/Towards%20a%20circular%20economy%3A%20Business%20rationale%20for%20an%20accelerated%20transition.pdf

Ellen MacArthur Foundation, & Granta Design. (2019). *Circularity Indicators: An Approach to Measuring Circularity* (Material Circularity Indicator (MCI), Issue. Ellen Macarthur Foundation. https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o

Emiliozzi, S., Ferriani, F., & Gazzani, A. (2024). *The European energy crisis and the consequences for the global natural gas market*. The Centre for Economic Policy Research (CEPR),. Retrieved 16/07/2024 from https://cepr.org/voxeu/columns/european-energy-crisis-and-consequences-global-natural-gas-market#:~:text=The%20European%20energy%20crisis%20and%20the%20consequences%20for%20the%20global%20natural%20gas%20market,-Simone%20Emiliozzi&text=The%202022%20Russian%20invasion%20of,focus%20shifted%20towards%20energy%20security.

Eppinger, E., Jain, A., Vimalnath, P., Gurtoo, A., Tietze, F., & Hernandez Chea, R. (2021). Sustainability transitions in manufacturing: the role of intellectual property. *Current Opinion in Environmental Sustainability*, *49*, 118-126. https://doi.org/10.1016/j.cosust.2021.03.018

ERN. (n.d.). *European Remanufacturing Network*. European Remanufacturing Network,. Retrieved 17/06/2024 from https://www.remanufacturing.eu/

Errington, M., & Childe, S. J. (2013). A business process model of inspection in remanufacturing. *Journal of Remanufacturing*, *3*(1), 1-22. https://doi.org/10.1186/2210-4690-3-7

ETSI. (2018). *Environmental Engineering (EE); Circular Economy (CE) in Information and Communication Technology (ICT); Definition of approaches, concepts and metrics* (ETSI TR 103 476 V1.1.2 (2018-02)). https://www.etsi.org/deliver/etsi_tr/103400_103499/103476/01.01.02_60/tr_103476v010102p.pdf

European Commission. (2023). *Study on the Critical Raw Materials for the EU 2023*. European Union. https://single-market-economy.ec.europa.eu/publications/study-critical-raw-materials-eu-2023-final-report_en

EUROSTAT. (2021). *End-of-life vehicle statistics*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=End-of-life_vehicle_statistics

Eurostat. (2023a). Contribution of recycled materials to raw materials demand - end-of-life recycling input rates (EOL-RIR). In (11/05/2023 ed.). European Union: European Union.

Eurostat. (2023b). EU self-sufficiency for raw materials. In (12/05/2023 ed.): European Union.

Eurostat. (2024). *Material flow accounts statistics - material footprints*. European Union. Retrieved 04/10/2024 from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Material_flow_accounts_statistics_-_material_footprints#EU.27s_material_footprint_by_material_category_over_time

Fariya, S., Gunbeyaz, S., Kurt, R., Sunaryo, S., & Djatmiko, E. (2019). Developing sustainable green ship recycling facilities in Indonesia: Investigation of current situation. Sustainable Development and Innovations in Marine Technologies: Proceedings of the 18th International Congress of the Maritme Association of the Mediterranean (IMAM 2019), September 9-11, 2019, Varna, Bulgaria,

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

Faye, N., & Butcher, A. (2023, 02/08/2023). *Unlocking Circularity: Maximising Value and Minimising Waste*. Wärtsila. Retrieved 12/07/2024 from https://www.wartsila.com/insights/article/unlocking-circularity-maximising-value-and-minimising-waste

Figge, F., Thorpe, A. S., Givry, P., Canning, L., & Franklin-Johnson, E. (2018). Longevity and Circularity as Indicators of Eco-Efficient Resource Use in the Circular Economy. *Ecological Economics*, *150*, 297-306. https://doi.org/10.1016/j.ecolecon.2018.04.030

Fofou, R. F., Jiang, Z., & Wang, Y. (2021). A Review on the Lifecycle Strategies Enhancing Remanufacturing. *Applied Sciences*, *11*(13), 5937. https://doi.org/10.3390/app11135937

Folger, R., & Stein, C. (2017). Abduction 101: Reasoning processes to aid discovery. *Human Resource Management Review*, *27*(2), 306-315. https://doi.org/10.1016/j.hrmr.2016.08.007

Fortune Business Insights. (2024). *Automotive Remanufacturing Market Size, Share & COVID-19 Impact Analysis, By Parts Type (Engine & Related Parts, Transmission Parts, Electrical & Electronics System Parts, Braking System Related Parts, Wheel & Suspension System Related Parts, and Others), By Vehicle Type (Passenger Cars and Commercial Vehicles), and Regional Forecast, 2023–2030* (FBI107428). https://www.fortunebusinessinsights.com/automotive-remanufacturing-market-107428

Franco, N. G., Almeida, M. F. L., & Calili, R. F. (2021). A strategic measurement framework to monitor and evaluate circularity performance in organizations from a transition perspective. *Sustainable Production and Consumption*, *27*, 1165-1182. https://doi.org/10.1016/j.spc.2021.02.017

Franklin-Johnson, E., Figge, F., & Canning, L. (2016). Resource duration as a managerial indicator for Circular Economy performance. *Journal of Cleaner Production*, *133*, 589-598. https://doi.org/10.1016/j.jclepro.2016.05.023

Frantlović, M., Jokić, I., & Jakovljević, M. M. (2016). Intelligent industrial instrumentation based on silicon MEMS pressure sensors. Sinteza 2016-International Scientific Conference on ICT and E-Business Related Research, Belgrade, Serbia.

Gao, S., Hakanen, E., & Rajala, R. (2020). Digital transformation: The interplay of explorative and exploitative capability development. 53rd Hawaii International Conference on System Sciences,

Gaspari, L., Colucci, L., Butzer, S., Colledani, M., & Steinhilper, R. (2017). Modularization in material flow simulation for managing production releases in remanufacturing. *Journal of Remanufacturing*, *7*(2), 139-157. https://doi.org/10.1007/s13243-017-0037-3

GCF Global. (2013). *Access 2013 -Getting Started with Access*. Retrieved 05/10/2023 from https://edu.gcfglobal.org/en/access2013/getting-started-with-access/1/

Geissdoerfer, M., Pieroni, M. P. P., Pigosso, D. C. A., & Soufani, K. (2020). Circular business models: A review. *Journal of Cleaner Production*, *277*, 123741. https://doi.org/10.1016/j.jclepro.2020.123741

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *J CLEAN PROD*, *143*, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Gertsakis, J., & Lewis, H. (2003). *Sustainability and the Waste Management Hierarchy*. https://www.helenlewisresearch.com.au/wp-content/uploads/2014/05/TZW_-_Sustainability_and_the_Waste_Hierarchy_2003.pdf

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11-32. https://doi.org/10.1016/j.jclepro.2015.09.007

Gilbert, P., Wilson, P., Walsh, C., & Hodgson, P. (2017). The role of material efficiency to reduce CO2 emissions during ship manufacture: A life cycle approach. *Marine Policy*, *75*, 227-237. https://doi.org/10.1016/j.marpol.2016.04.003

Goepel, K. D. (2013). Implementing the analytic hierarchy process as a standard method for multi-criteria decision making in corporate enterprises–a new AHP excel template with multiple inputs. Proceedings of the international symposium on the analytic hierarchy process,

Goltens. (n.d.-a). *End to end restoration of MaK 12M282 after casualty*. Retrieved 11/03/2022 from https://www.goltens.com/resources/mak-marine-engine-case-study-mak-12m282/

Goltens. (n.d.-b). *Marine*. Retrieved 11/03/2022 from https://www.goltens.com/industries-2/marine/

Gong, Q., Xiong, Y., Jiang, Z., Yang, J., & Chen, C. (2022). Timing Decision for Active Remanufacturing Based on 3E Analysis of Product Life Cycle. *Sustainability*, *14*(14), 8749. https://www.mdpi.com/2071-1050/14/14/8749

Gong, Y., Putnam, E., You, W., & Zhao, C. (2020). Investigation into circular economy of plastics: The case of the UK fast moving consumer goods industry. *Journal of Cleaner Production*, *244*, 118941. https://doi.org/10.1016/j.jclepro.2019.118941

Gössling, S., Meyer-Habighorst, C., & Humpe, A. (2021). A global review of marine air pollution policies, their scope and effectiveness. *Ocean & Coastal Management*, *212*, 105824. https://doi.org/10.1016/j.ocecoaman.2021.105824

Göswein, V., Carvalho, S., Cerqueira, C., & Lorena, A. (2022). Circular material passports for buildings–Providing a robust methodology for promoting circular buildings. IOP Conference Series: Earth and Environmental Science,

Govindan, K., & Hasanagic, M. (2018). A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. *International Journal of Production Research*, *56*(1-2), 278-311. https://doi.org/10.1080/00207543.2017.1402141

Grafström, J., & Aasma, S. (2021). Breaking circular economy barriers. *Journal of Cleaner Production*, *292*, 126002. https://doi.org/10.1016/j.jclepro.2021.126002

Groupe Renault. (2022). *Refactory Flins*. Groupe Renault. https://www.renaultgroup.com/wp-content/uploads/2022/05/202203_rg_plaquette_refactory_12_en.pdf

Gualeni, P., & Maggioncalda, M. (2018). Life cycle ship performance assessment (LCPA): A blended formulation between costs and environmental aspects for early design stage. *International Shipbuilding Progress*, *65*, 127-147. https://doi.org/10.3233/ISP-180144

Guide, D., & Van Wassenhove, L. (2001). Managing Product Returns for Remanufacturing. *Production and Operations Management*, *10*. https://doi.org/10.1111/j.1937-5956.2001.tb00075.x

Guide, D., & Van Wassenhove, L. (2002). The reverse supply chain. *Harvard Business Review*, *80*, 25-26.

Gunbeyaz, S. A. (2019). *Designing efficient and contemporary ship recycling yards through discrete event simulation* University of Strathclyde]. Glasgow.

Gunbeyaz, S. A., Kurt, R. E., & Turan, O. (2020). Investigation of different cutting technologies in a ship recycling yard with simulation approach. *Ships and Offshore Structures*, 1-13. https://doi.org/10.1080/17445302.2020.1846916

Guo, Q., & Guo, T. (2024). Research on the competitive landscape of global rare earth resources demand. *Managerial and Decision Economics*, *45*(5), 3217-3238. https://doi.org/10.1002/mde.4187

Gupta, J., Liverman, D., Prodani, K., Aldunce, P., Bai, X., Broadgate, W., Ciobanu, D., Gifford, L., Gordon, C., Hurlbert, M., Inoue, C. Y. A., Jacobson, L., Kanie, N., Lade, S. J., Lenton, T. M., Obura, D., Okereke, C., Otto, I. M., Pereira, L., . . . Verburg, P. H. (2023). Earth system justice needed to identify and live within Earth system boundaries. *Nature Sustainability*, *6*(6), 630-638. https://doi.org/10.1038/s41893-023-01064-1

Gupta, S., Chen, H., Hazen, B. T., Kaur, S., & Santibañez Gonzalez, E. D. R. (2019). Circular economy and big data analytics: A stakeholder perspective. *Technological Forecasting and Social Change*, *144*, 466-474. https://doi.org/10.1016/j.techfore.2018.06.030

Han, X., Wu, H., Yang, Q., & Shang, J. (2017). Collection channel and production decisions in a closed-loop supply chain with remanufacturing cost disruption. *International Journal of Production Research*, *55*(4), 1147-1167. https://doi.org/10.1080/00207543.2016.1230684

Hapuwatte, B. M., & Jawahir, I. S. (2021). Closed-loop sustainable product design for circular economy. *Journal of Industrial Ecology*, *25*(6), 1430-1446. https://doi.org/10.1111/jiec.13154

Hapuwatte, B. M., Seevers, K. D., & Jawahir, I. S. (2022). Metrics-based dynamic product sustainability performance evaluation for advancing the circular economy. *Journal of Manufacturing Systems*, *64*, 275-287. https://doi.org/10.1016/j.jmsy.2022.06.013

Hashemi, V., Chen, M., & Fang, L. (2016). Modeling and analysis of aerospace remanufacturing systems with scenario analysis. *The International Journal of Advanced Manufacturing Technology*, *87*(5), 2135-2151. https://doi.org/10.1007/s00170-016-8566-8

Henckens, M. L. C. M., Driessen, P. P. J., & Worrell, E. (2014). Metal scarcity and sustainability, analyzing the necessity to reduce the extraction of scarce metals. *Resources, Conservation and Recycling*, *93*, 1-8. https://doi.org/10.1016/j.resconrec.2014.09.012

Herrero-Luna, S., Ferrer-Serrano, M., & Pilar Latorre-Martinez, M. (2022). Circular Economy and Innovation: A Systematic Literature Review. *Central European Business Review*, *11*(1), 65-84. https://doi.org/10.18267/j.cebr.275

Hiremath, A. M., Pandey, S. K., Kumar, D., & Asolekar, S. R. (2014). Ecological Engineering, Industrial Ecology and Eco-Industrial Networking Aspects of Ship Recycling Sector in India. *APCBEE Procedia*, *10*, 159-163. https://doi.org/10.1016/j.apcbee.2014.10.035

Hiremath, A. M., Tilwankar, A. K., & Asolekar, S. R. (2015). Significant steps in ship recycling vis-a-vis wastes generated in a cluster of yards in Alang: a case study. *Journal of Cleaner Production*, *87*, 520-532. https://doi.org/10.1016/j.jclepro.2014.09.031

Honic, M., Kovacic, I., Aschenbrenner, P., & Ragossnig, A. (2021). Material Passports for the end-of-life stage of buildings: Challenges and potentials. *Journal of Cleaner Production*, *319*, 128702. https://doi.org/10.1016/j.jclepro.2021.128702

Hoosain, M. S., Paul, B. S., & Ramakrishna, S. (2020). The impact of 4IR digital technologies and circular thinking on the United Nations sustainable development goals. *Sustainability*, *12*(23), 10143. https://doi.org/10.3390/su122310143

Hossain, M. S., Fakhruddin, A. N. M., Chowdhury, M. A. Z., & Gan, S. H. (2016). Impact of ship-Breaking activities on the coastal environment of Bangladesh and a management system for its sustainability. *Environmental Science & Policy*, *60*, 84-94. https://doi.org/10.1016/j.envsci.2016.03.005

HOUSEFUL. (2019). *D2. 3: Reference methodologies and KPIs in circular economy analysis WP2, T2. 3.* https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c8e38027&appId=PPGMS

Hrytsiuk, P., Parfeniuk, O., & Shevchenko, I. (2023). The logistic dynamics of population growth as a prerequisite for global sustainable development. *IOP Conference Series: Earth and Environmental Science*, *1126*(1), 012030. https://doi.org/10.1088/1755-1315/1126/1/012030

Hu, Y., Chen, L., Chi, Y., & Song, B. (2022). Manufacturer encroachment on a closed-loop supply chain with design for remanufacturing. *Managerial and Decision Economics*, *43*(6), 1941-1959. https://doi.org/10.1002/mde.3501

Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., & De Meester, S. (2017). Performance indicators for a circular economy: A case study on post-industrial plastic waste. *Resources, Conservation and Recycling*, *120*, 46-54. https://doi.org/10.1016/j.resconrec.2017.01.013

Huysman, S., Debaveye, S., Schaubroeck, T., Meester, S. D., Ardente, F., Mathieux, F., & Dewulf, J. (2015). The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders. *Resources, Conservation and Recycling*, *101*, 53-60. https://doi.org/10.1016/j.resconrec.2015.05.014

Hyvärinen, M., Pylkkö, M., & Kärki, T. (2023). Closed-Loop Recycling and Remanufacturing of Polymeric Aircraft Parts. *Journal of Composites Science*, *7*(3), 121. https://doi.org/10.3390/jcs7030121

IACS. (2022). Requirements concerning machinery installations. In *International Association of Classification Societies* (Vol. IACS Req. 1982/Rev.10 2021/Corr.1 2022): IACS.

Ibáñez-Forés, V., Martínez-Sánchez, V., Valls-Val, K., & Bovea, M. D. (2022). Sustainability reports as a tool for measuring and monitoring the transition towards the circular economy of organisations: Proposal of indicators and metrics. *Journal of Environmental Management*, *320*, 115784. https://doi.org/10.1016/j.jenvman.2022.115784

Ibáñez-Forés, V., Martínez-Sánchez, V., Valls-Val, K., & Bovea, M. D. (2023). How do organisations communicate aspects related to their social performance? A proposed set of indicators and metrics for sustainability reporting. *Sustainable Production and Consumption*, *35*, 157-172. https://doi.org/10.1016/j.spc.2022.10.024

IBM. (2024). *IBM - What is Big Data Analytics?* Retrieved 16/06/2022 from https://www.ibm.com/topics/big-data-analytics

ILO. (2004). *Safety and health in shipbreaking: Guidelines for Asian countries and Turkey*. International Labour Organization. http://www.ilo.org/public/english/standards/relm/gb/docs/gb289/pdf/meshs-1.pdf

IMO-NORAD. (2015). *Safe and environmentally sound ship recycling SENSREC, WP4, Part I.*

IMO. (2009). *The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships*. Retrieved 13/12/2023 from https://www.imo.org/en/about/Conventions/pages/the-hong-kong-international-convention-for-the-safe-and-environmentally-sound-recycling-of-ships.aspx

IMO. (2018a). *Resolution MEPC.304(72), Initial IMO Strategy on Reduction of GHG Emissions from Ships*. International Maritime Organization. https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304(72).pdf

IMO. (2018b). UN body adopts climate change strategy for shipping. In. IMO London: International Maritime Organization,.

IMO. (2023). *Resolution MEPC.377(80), 2023 IMO Strategy on Reduction of GHG Emissions from Ships*. International Maritime Organization. https://wwwcdn.imo.org/localresources/en/MediaCentre/PressBriefings/Documents/Clean%20version%20of%20Annex%201.pdf

Infomaritime EU. (2021). *World merchant fleet and top 15 shipowning countries*. Retrieved December from http://infomaritime.eu/index.php/2021/08/22/top-15-shipowning-countries/

IRP. (2018). *Re-defining Value – The Manufacturing Revolution. Remanufacturing, Refurbishment, Repair and Direct Reuse in the Circular Economy.* (Nabil Nasr, Jennifer Russell, Stefan Bringezu, Stefanie Hellweg, Brian Hilton, Cory Kreiss, and Nadia von Gries, Issue. International Resource Panel (IRP). https://www.resourcepanel.org/reports/re-defining-value-manufacturing-revolution

ISO. (2024a). Measuring and assessing circularity performance. In *Circular economy* (Vol. 59020:2024). Switzerland: International Organization for Standardization.

ISO. (2024b). Vocabulary, principles and guidance for implementation. In *Circular economy* (Vol. 59004:2024). Switzerland: International Organization for Standardization.

Jäger-Roschko, M., & Petersen, M. (2022). Advancing the circular economy through information sharing: A systematic literature review. *Journal of Cleaner Production*, *369*, 133210. https://doi.org/10.1016/j.jclepro.2022.133210

Jansson, K. (2016). Circular Economy in Shipbuilding and Marine Networks – A Focus on Remanufacturing in Ship Repair. In H. Afsarmanesh, L. M. Camarinha-Matos, & A. Lucas Soares (Eds.), *Collaboration in a Hyperconnected World: 17th IFIP WG 5.5 Working Conference on Virtual Enterprises, PRO-VE 2016, Porto, Portugal, October 3-5, 2016, Proceedings* (pp. 661-671). Springer International Publishing. https://doi.org/10.1007/978-3-319-45390-3_57

Jawahir, I. S., & Bradley, R. (2016). Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing. *Procedia CIRP*, *40*, 103-108. https://doi.org/10.1016/j.procir.2016.01.067

Jensen, H. H., Andersen, M. M., Dao, A., Lind, M., Pandey, V., Bapuji, G., Petersen, M., Hobson, B., Lehmacher, W., & Turos, A. (2021). Digitalisation in a Maritime Circular Economy. In M. Lind, M. Michaelides, R. Ward, & R. T. Watson (Eds.), *Maritime Informatics: Additional Perspectives and Applications* (pp. 17-37). Springer International Publishing. https://doi.org/10.1007/978-3-030-72785-7_2

Jensen, J. P., & Remmen, A. (2017). Enabling Circular Economy Through Product Stewardship. *Procedia Manufacturing*, *8*, 377-384. https://doi.org/10.1016/j.promfg.2017.02.048

Jerome, A., Helander, H., Ljunggren, M., & Janssen, M. (2022). Mapping and testing circular economy product-level indicators: A critical review. *Resources,* *Conservation and Recycling*, *178*, 106080. https://doi.org/10.1016/j.resconrec.2021.106080

Jia, F., Yin, S., Chen, L., & Chen, X. (2020). The circular economy in the textile and apparel industry: A systematic literature review. *Journal of Cleaner Production*, *259*, 120728. https://doi.org/10.1016/j.jclepro.2020.120728

Joensuu, R., Boorsma, N., & Peck, D. (2023). *Remanufacturing for the maritime industry – white paper*. Delft University of Technology. https://maritimeremanufacturingnetwork.com/tu-delft-a-great-opportunity-to-achieve-sustainability-quickly/

Kalmykova, Y., Sadagopan, M., & Rosado, L. (2018). Circular economy – From review of theories and practices to development of implementation tools. *Resources, Conservation and Recycling*, *135*, 190-201. https://doi.org/10.1016/j.resconrec.2017.10.034

Kalsoom, T., Ramzan, N., Ahmed, S., & Ur-Rehman, M. (2020). Advances in Sensor Technologies in the Era of Smart Factory and Industry 4.0. *Sensors*, *20*(23), 6783. https://doi.org/10.3390/s20236783

Karvonen, I., Jansson, K., Tonteri, H., Vatanen, S., & Uoti, M. (2015). Enhancing remanufacturing–studying networks and sustainability to support Finnish industry. *Journal of Remanufacturing*, *5*(1), 1-16. https://doi.org/10.1186/s13243-015-0015-6

Keivanpour, S., Ait-Kadi, D., & Mascle, C. (2013). Toward a strategic approach to End-of-Life aircraft recycling projects. *Journal of Management and Sustainability*, *3*, 76. https://doi.org/10.5539/jms.v3n3p76

Keivanpour, S., Ait Kadi, D., & Mascle, C. (2015). End of life aircrafts recovery and green supply chain (a conceptual framework for addressing opportunities and challenges). *Management Research Review*, *38*(10), 1098-1124. https://doi.org/10.1108/MRR-11-2014-0267

Kerin, M., & Pham, D. T. (2019). A review of emerging industry 4.0 technologies in remanufacturing. *Journal of Cleaner Production*, *237*, 117805. https://doi.org/10.1016/j.jclepro.2019.117805

Kerin, M., & Pham, D. T. (2020). Smart remanufacturing: a review and research framework. *Journal of Manufacturing Technology Management*, *31*(6), 1205-1235. https://doi.org/10.1108/JMTM-06-2019-0205

Khan, M., Mittal, S., West, S., & Wuest, T. (2018). Review on upgradability – A product lifetime extension strategy in the context of product service systems. *Journal of Cleaner Production*, *204*, 1154-1168. https://doi.org/10.1016/j.jclepro.2018.08.329

King, A. M., Burgess, S. C., Ijomah, W., & McMahon, C. A. (2006). Reducing waste: repair, recondition, remanufacture or recycle? *Sustainable Development*, *14*(4), 257-267. https://doi.org/10.1002/sd.271

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005

Koehler, D. C. F. (2021). *APRA Europe News - August 2021*. Automotive Parts Remanufacturers Association (APRA),. Retrieved 15/11/2021 from https://apraeurope.org/wp-content/uploads/2021/08/20210823-APRA-Europe-News-Edition-21.pdf

Köhler, J., Sönnichsen, S. D., & Beske-Jansen, P. (2022). Towards a collaboration framework for circular economy: The role of dynamic capabilities and open innovation. *Business strategy and the environment*, *31*(6), 2700-2713. https://doi.org/10.1002/bse.3000

Kok, L., Wurpel, G., & Ten Wolde, A. (2013). *Unleashing the Power of the Circular Economy*. https://www.osti.gov/etdeweb/servlets/purl/22174941

Kong, X., Feng, K., Wang, P., Wan, Z., Lin, L., Zhang, N., & Li, J. (2022). Steel stocks and flows of global merchant fleets as material base of international trade from 1980 to 2050. *Global Environmental Change*, *73*, 102493. https://doi.org/10.1016/j.gloenvcha.2022.102493

Konietzko, J., Bocken, N., & Hultink, E. J. (2019). Online Platforms and the Circular Economy. In N. Bocken, P. Ritala, L. Albareda, & R. Verburg (Eds.), *Innovation for Sustainability: Business Transformations Towards a Better World* (pp. 435-450). Springer International Publishing. https://doi.org/10.1007/978-3-319-97385-2_23

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular Economy: The Concept and its Limitations. *Ecological Economics*, *143*, 37-46. https://doi.org/10.1016/j.ecolecon.2017.06.041

Kravchenko, M., Pigosso, D. C. A., & McAloone, T. C. (2019). Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators. *Journal of Cleaner Production*, *241*, 118318. https://doi.org/10.1016/j.jclepro.2019.118318

Kristensen, H. S., & Mosgaard, M. A. (2020). A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? *Journal of Cleaner Production*, *243*, 118531. https://doi.org/10.1016/j.jclepro.2019.118531

Kristoffersen, E., Mikalef, P., Blomsma, F., & Li, J. (2021). Towards a business analytics capability for the circular economy. *Technological Forecasting and Social Change*, *171*, 120957. https://doi.org/https://doi.org/10.1016/j.techfore.2021.120957

Kurt, R. E., & Gunbeyaz, S. A. (2020). *IMO SENSREC Project Report - Safe and Environmentally Sound Ship Recycling in Bangladesh*. https://pureportal.strath.ac.uk/en/projects/imo-sensrec-full-scale-training-delivery-in-bangladesh

Kurt, R. E., McKenna, S. A., Gunbeyaz, S. A., & Turan, O. (2017). Investigation of occupational noise exposure in a ship recycling yard. *Ocean Engineering*, *137*, 440-449. https://doi.org/10.1016/j.oceaneng.2017.03.040

Kwak, M., & Kim, H. (2017). Green profit maximization through integrated pricing and production planning for a line of new and remanufactured products. *Journal of Cleaner Production*, *142*, 3454-3470. https://doi.org/10.1016/j.jclepro.2016.10.121

Lehmann, C., Cruz-Jesus, F., Oliveira, T., & Damásio, B. (2022). Leveraging the circular economy: Investment and innovation as drivers. *Journal of Cleaner Production*, *360*, 132146. https://doi.org/10.1016/j.jclepro.2022.132146

Li, Q., Han, Y., Liu, X., Ansari, U., Cheng, Y., & Yan, C. (2022). Hydrate as a by-product in CO2 leakage during the long-term sub-seabed sequestration and its role in preventing further leakage. *Environmental Science and Pollution Research*, *29*(51), 77737-77754. https://doi.org/10.1007/s11356-022-21233-7

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: a comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, *115*, 36-51. https://doi.org/10.1016/j.jclepro.2015.12.042

Linder, M., Sarasini, S., & van Loon, P. (2017). A Metric for Quantifying Product-Level Circularity. *Journal of Industrial Ecology*, *21*(3), 545-558. https://doi.org/10.1111/jiec.12552

Linder, M., & Williander, M. (2017). Circular business model innovation: inherent uncertainties. *Business strategy and the environment*, *26*(2), 182-196. https://doi.org/10.1002/bse.1906

Lindstad, E., Polic, D., Rialland, A., Sandaas, I., & Stokke, T. (2023). Reaching IMO 2050 GHG Targets Exclusively Through Energy Efficiency Measures. *Journal of Ship Production and Design*, *39*(04), 194-204. https://doi.org/10.5957/jspd.10220024

Lloyd's Register. (2022). *Rules and Regulations for the Classification of Ships*.

Lopes de Sousa Jabbour, A. B., Jabbour, C. J. C., Godinho Filho, M., & Roubaud, D. (2018). Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. *Annals of Operations Research*, *270*(1), 273-286. https://doi.org/10.1007/s10479-018-2772-8

Lund, R. T. (1984). Remanufacturing. *Technology review*, *87*(2), 19-23, 28-29. https://www.scopus.com/inward/record.uri?eid=2-s2.0-0021370421&partnerID=40&md5=50c4c13ef59873b461543794 80d86d07

Luoma, P., Toppinen, A., & Penttinen, E. (2021). The Role and Value of Data in Circular Business Models–a Systematic Literature Review. *Journal of business models*, *9*(2), 44-71. https://doi.org/10.5278/jbm.v9i2.3448

MacArthur, E. (2013). Towards the circular economy. *Journal of Industrial Ecology*, *2*, 23-44.

Marques-McEwan, M., & Bititci, U. S. (2023). Understanding the Implications of Circular Business Models for Businesses and Supply Chains. Advances in Production Management Systems. Production Management Systems for Responsible Manufacturing, Service, and Logistics Futures, Cham.

Marques, M. C., Bititci, U. S., & Haniff, A. P. (2021). How Is Value Created in the Circular Economy? Evidence from Remanufacturing and Repair Businesses. Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems, Cham.

Masoumi, S. M., Kazemi, N., & Abdul-Rashid, S. H. (2019). Sustainable Supply Chain Management in the Automotive Industry: A Process-Oriented Review. *Sustainability*, *11*(14). https://doi.org/10.3390/su11143945

Mathew, E. (2021). Ship recycling, market imperfections and the relevance of a consortium of ship recycling nations in the Indian subcontinent. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, *5*(2), 23-31. https://doi.org/10.1080/25725084.2021.1921994

Matsumoto, M., & Umeda, Y. (2011). An analysis of remanufacturing practices in Japan. *Journal of Remanufacturing*, *1*(1), 1-11. https://doi.org/10.1186/2210-4690-1-2

McKenna, S. A., Kurt, R. E., & Turan, O. (2012). A methodology for a 'design for ship recycling'. In *The Environmentally Friendly Ship* (pp. 37-44). Royal Institution of Naval Architects. http://www.scopus.com/inward/record.url?scp=84864885193&partnerID=8YFLogxK

MEE. (2018). *Announcement on adjustment to the catalogue for the administration of import solid waste. Announcement No. 6*. Ministry of Ecology and Environment. https://images.magnetmail.net/images/clients/ISRIID/attach/MEEAnnouncement20182019BannedItems.pdf.

Meng, K., Lou, P., Peng, X., & Prybutok, V. (2016). A hybrid approach for performance evaluation and optimized selection of recoverable end-of-life products in the reverse supply chain. *Computers & Industrial Engineering*, *98*, 171-184. https://doi.org/10.1016/j.cie.2016.05.025

Merkisz-Guranowska, A. (2017). Product recycling of automotive parts – trends and issues [journal article]. *Combustion Engines*, *171*(4), 24-28. https://doi.org/10.19206/ce-2017-404

Mesa, J., Esparragoza, I., & Maury, H. (2018). Developing a set of sustainability indicators for product families based on the circular economy model. *Journal of Cleaner Production*, *196*, 1429-1442. https://doi.org/10.1016/j.jclepro.2018.06.131

MIA. (2018). *Revised rules and regulations implementing republic act no. 9295, entitled "An act promoting the development of Philippine domestic shipping, shipbuilding, and ship repair and ship breaking, ordaining reforms in government policies towards shipping in the Philippines, and for other purposes."*. Republic of the Philippines: Maritime Industry Authority (MIA), Retrieved from https://marina.gov.ph/wp-content/uploads/2018/06/Revised-IRR-of-RA-9295.pdf

Michelini, G., Moraes, R. N., Cunha, R. N., Costa, J. M. H., & Ometto, A. R. (2017). From Linear to Circular Economy: PSS Conducting the Transition. *Procedia CIRP*, *64*, 2-6. https://doi.org/10.1016/j.procir.2017.03.012

Milios, L., Beqiri, B., Whalen, K. A., & Jelonek, S. H. (2019). Sailing towards a circular economy: Conditions for increased reuse and remanufacturing in the Scandinavian maritime sector. *Journal of Cleaner Production*, *225*, 227-235. https://doi.org/10.1016/j.jclepro.2019.03.330

Miller, A. M., Alvarez, R., & Hartman, N. (2018). Towards an extended model-based definition for the digital twin. *Computer-Aided Design and Applications*, *15*(6), 880-891. https://doi.org/10.1080/16864360.2018.1462569

Mishra, R., Singh, R. K., & Govindan, K. (2022). Barriers to the adoption of circular economy practices in Micro, Small and Medium Enterprises: Instrument development, measurement and validation. *Journal of Cleaner Production*, *351*, 131389. https://doi.org/10.1016/j.jclepro.2022.131389

Mitchell, P., & James, K. (2015). Economic growth potential of more circular economies. *Waste and Resources Action Programme (WRAP): Banbury, UK*.

Mohammad, W., Elomri, A., & Kerbache, L. (2022). The Global Semiconductor Chip Shortage: Causes, Implications, and Potential Remedies. *IFAC-PapersOnLine*, *55*(10), 476-483. https://doi.org/10.1016/j.ifacol.2022.09.439

Montwiłł, A., Kasińska, J., & Pietrzak, K. (2018). Importance of key phases of the ship manufacturing system for efficient vessel life cycle management. *Procedia Manufacturing*, *19*, 34-41. https://doi.org/10.1016/j.promfg.2018.01.006

mtu. (2019). Factory Reman and Overhaul Solutions - Good As New. In m.-R. Royce (Ed.). Germany.

mtu. (n.d.-a). *Reman & Overhaul Solutions*. Retrieved 19/08/2023 from https://www.mtu-solutions.com/eu/en/service/reman-and-overhaul-solutions.html

mtu. (n.d.-b). *Remanufactured Solutions*. Retrieved 19/08/2023 from https://www.mtu-solutions.com/eu/en/service/reman-and-overhaul-solutions/remanufacture.html?wcmmode=296

Mulhall, D., Ayed, A.-C., Schroeder, J., Hansen, K., & Wautelet, T. (2022). The product circularity data sheet—a standardized digital fingerprint for circular economy data about products. *Energies*, *15*(9), 3397. https://doi.org/10.3390/en15093397

Murray, A., Skene, K., & Haynes, K. (2017). The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*(3), 369-380. https://doi.org/10.1007/s10551-015-2693-2

Nasr, N., & Thurston, M. (2006). Remanufacturing: A key enabler to sustainable product systems. *Rochester Institute of Technology*, *23*.

Neşer, G., Ünsalan, D., Tekoğul, N., & Stuer-Lauridsen, F. (2008). The shipbreaking industry in Turkey: environmental, safety and health issues. *Journal of Cleaner Production*, *16*(3), 350-358. https://doi.org/10.1016/j.jclepro.2006.08.018

Neves, S. A., & Marques, A. C. (2022). Drivers and barriers in the transition from a linear economy to a circular economy. *Journal of Cleaner Production*, *341*, 130865. https://doi.org/10.1016/j.jclepro.2022.130865

NGO Ship Breaking Platform. (2022). *Impact Report 2020-2021*. NGO Ship Breaking Platform. https://shipbreakingplatform.org/wp-content/uploads/2022/11/NGO-SBP-Annual-Report-2020_2021.pdf

NSO. (2022). *National Shipbuilding Strategy*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/

attachment_data/file/1061201/_CP_605___National_Shipbuilding_Strategy_Refresh.pdf

OECD. (2023). *Ocean shipping and shipbuilding*. Organisation for Economic Cooperation and Development (OECD). Retrieved 07/10/2023 from https://www.oecd.org/ocean/topics/ocean-shipping/

Oikonomou, F., Alhaddad, A., Kontopoulos, I., Makris, A., Tserpes, K., Arampatzi, P., Bonazountas, M., Ocampo, H. R., Demetriou, G., Katusic, V., & Dober, D. (2021, 14-16 July 2021). Data Driven Fleet Monitoring and Circular Economy. 2021 17th International Conference on Distributed Computing in Sensor Systems (DCOSS),

Okumus, D., Andrews, E., & Gunbeyaz, S. A. (2024a). Developing circularity metrics for the maritime industry: A stakeholder focused study. *Ocean Engineering*, *312*, 119158. https://doi.org/10.1016/j.oceaneng.2024.119158

Okumus, D., Gunbeyaz, S. A., & Karamperidis, S. (2023a). *Potential Impact of the Circular Economy Concept in Maritime Transport* (White Paper - Circular Economy Network+ in Transportation Systems, Issue. University of Warwick. https://warwick.ac.uk/fac/sci/wmg/research/materials/smam/cents/activities/whitepapers/maritime.pdf

Okumus, D., Gunbeyaz, S. A., Kurt, R. E., & Turan, O. (2023b). Circular economy approach in the maritime industry: Barriers and the path to sustainability. *Transportation Research Procedia*, *72*, 2157-2164. https://doi.org/10.1016/j.trpro.2023.11.701

Okumus, D., Gunbeyaz, S. A., Kurt, R. E., & Turan, O. (2023c). Towards a circular maritime industry: Identifying strategy and technology solutions. *Journal of Cleaner Production*, *382*, 134935. https://doi.org/10.1016/j.jclepro.2022.134935

Okumus, D., Gunbeyaz, S. A., Kurt, R. E., & Turan, O. (2024b). An Approach to Advance Circular Practices in the Maritime Industry through a Database as a Bridging Solution. *Sustainability*, *16*(1), 453. https://doi.org/10.3390/su16010453

Okumus, D., Gunbeyaz, S. A., Kurt, R. E., Turan, O., Canbulat, O., & Giagloglou, E. (2022). *Circular Economy- Increased Value Extraction from End of Life*

Marine Assets (CENTS: Circular Economy Network+ in Transportation Systems, Issue Project Report). https://pureportal.strath.ac.uk/en/projects/cents-circular-economy-network-in-transportation-systems-maritime

Opferkuch, K., Walker, A. M., Roos Lindgreen, E., Caeiro, S., Salomone, R., & Ramos, T. B. (2023). Towards a framework for corporate disclosure of circular economy: Company perspectives and recommendations. *Corporate Social Responsibility and Environmental Management*, *30*(5), 2457-2474. https://doi.org/10.1002/csr.2497

ORACLE. (2020). *Oracle. What is a database?*. Retrieved 12/01/2022 from https://www.oracle.com/uk/database/what-is-database/

Oraiopoulos, N., Ferguson, M. E., & Toktay, L. B. (2012). Relicensing as a Secondary Market Strategy. *Management Science*, *58*(5), 1022-1037. https://doi.org/10.1287/mnsc.1110.1456

Ortiz-de-Montellano, C. G.-S., Samani, P., & van der Meer, Y. (2023). How can the circular economy support the advancement of the Sustainable Development Goals (SDGs)? A comprehensive analysis. *Sustainable Production and Consumption*, *40*, 352-362. https://doi.org/10.1016/j.spc.2023.07.003

OSHA. (2010). *Safe Work Practices for Shipbreaking*. https://www.osha.gov/Publications/3375shipbreaking.pdf

Östlin, J. (2008). *On remanufacturing systems: analysing and managing material flows and remanufacturing processes* Institutionen för ekonomisk och industriell utveckling].

Parker, D., Riley, K., Robinson, S., Symington, H., Tewson, J., Jansson, K., Ramkumar, S., & Peck, D. (2015). *Remanufacturing market study* (Ref. Ares (2015)5923139). European Commission. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5a4bc7898&appId=PPGMS

Patti, S. (2023). Eco-efficiency, Circularity Measurement and Assessment. In S. Patti (Ed.), *Circular Economy and Policy: Sustainability, Environmental, and Social Perspectives* (pp. 137-161). Springer International Publishing. https://doi.org/10.1007/978-3-031-43324-5_7

Pearce, D. W., & Turner, R. K. (1990). *Economics of natural resources and the environment*. JHU press.

Peng, S., Yang, Y., Li, T., Smith, T. M., Tan, G. Z., & Zhang, H.-C. (2019). Environmental Benefits of Engine Remanufacture in China's Circular Economy Development. *Environmental Science & Technology*, *53*(19), 11294-11301. https://doi.org/10.1021/acs.est.9b02973

PlanetLabs. (2017). Retrieved 08/10/2024 from https://planetgallery.global.ssl.fastly.net/full/alang-20170323-full.jpg

Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). *Circular Economy: Measuring innovation in the product chain*. PBL Netherlands Environmental Assessment Agency PBL Publishers.

Pournara, A., & Sakkas, V. (2021). *Shipyards and Ship breaking: Opportunities for utilization of steel under the prism of Circular Economy* 17th International Conference on Environmental Science and Technology, Athens. https://www.researchgate.net/profile/Anthi_Pournara/publication/354374741_Shipyards_and_Ship_breaking_Opportunities_for_utilization_of_steel_under_the_prism_of_Circular_Economy/links/6313c903acd814437f011002/Shipyards-and-Ship-breaking-Opportunities-for-utilization-of-steel-under-the-prism-of-Circular-Economy.pdf

Preston, F. (2012). *A global redesign? Shaping the circular economy*. Chatham House. http://biblioteca.fundacionicbc.edu.ar/images/d/d7/Bp0312_preston.pdf

Radhi, M., & Zhang, G. (2016). Optimal configuration of remanufacturing supply network with return quality decision. *International Journal of Production Research*, *54*(5), 1487-1502. https://doi.org/10.1080/00207543.2015.1086034

Rajala, R., Hakanen, E., Mattila, J., Seppälä, T., & Westerlund, M. (2018). How Do Intelligent Goods Shape Closed-Loop Systems? *California Management Review*, *60*(3), 20-44. https://doi.org/10.1177/0008125618759685

Ramalho, J., Correia, S., Fu, L., António, L., Brites, C., André, P., Ferreira, R., & Carlos, L. (2019). Luminescence Thermometry on the Route of the Mobile-Based Internet of Things (IoT): How Smart QR Codes Make It Real. *Advanced Science*, *6*, 1900950. https://doi.org/10.1002/advs.201900950

Razmjooei, D., Alimohammadlou, M., Ranaei Kordshouli, H.-A., & Askarifar, K. (2024). A bibliometric analysis of the literature on circular economy and sustainability in maritime studies. *Environment, Development and Sustainability*, *26*(3), 5509-5536. https://doi.org/10.1007/s10668-023-02942-6

Reike, D., Vermeulen, W. J. V., & Witjes, S. (2018). The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. *Resources, Conservation and Recycling*, *135*, 246-264. https://doi.org/10.1016/j.resconrec.2017.08.027

Repp, L., Hekkert, M., & Kirchherr, J. (2021). Circular economy-induced global employment shifts in apparel value chains: Job reduction in apparel production activities, job growth in reuse and recycling activities. *Resources, Conservation and Recycling*, *171*, 105621. https://doi.org/10.1016/j.resconrec.2021.105621

RETROFIT. (2015). *Final Report Summary - RETROFIT (RETROFITting ships with new technologies for improved overall environmental footprint)*. https://cordis.europa.eu/project/id/285420/reporting

RIC. (2024). *Impacts of Remanufacturing*. Remanufacturing Industries Council,. Retrieved 17/06/2024 from https://remancouncil.org/impacts-of-remanufacturing/

Rincón-Moreno, J., Ormazábal, M., Álvarez, M. J., & Jaca, C. (2021). Advancing circular economy performance indicators and their application in Spanish companies. *Journal of Cleaner Production*, *279*, 123605. https://doi.org/10.1016/j.jclepro.2020.123605

Rommel, Y. (2018). *The circular economy in the automotive sector: How far can we introduce it?* Victanis Advisory Services GmbH. Retrieved 26 October from https://www.victanis.com/blog/circular-economy-automotive-industry

Roos, G. (2014). Business model innovation to create and capture resource value in future circular material chains. *Resources*, *3*(1), 248-274. https://doi.org/10.3390/resources3010248

Rosa, P., Sassanelli, C., & Terzi, S. (2019). Towards Circular Business Models: A systematic literature review on classification frameworks and archetypes.

Journal of Cleaner Production, *236*, 117696. https://doi.org/10.1016/j.jclepro.2019.117696

Saaty, T. L. (1980). *The analytic hierarchy process : planning, priority setting, resource allocation*. New York, London : McGraw-Hill International Book Co.

Saidani, M., Yannou, B., Leroy, Y., & Cluzel, F. (2017). How to Assess Product Performance in the Circular Economy? Proposed Requirements for the Design of a Circularity Measurement Framework. *Recycling*, *2*(1), 6. https://doi.org/10.3390/recycling2010006

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production*, *207*, 542-559. https://doi.org/10.1016/j.jclepro.2018.10.014

Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019). Circular economy performance assessment methods: A systematic literature review. *Journal of Cleaner Production*, *229*, 440-453. https://doi.org/10.1016/j.jclepro.2019.05.019

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (8th ed.). Harlow: Pearson.

Schaubroeck, S., Dewil, R., & Allacker, K. (2022). Circularity and LCA-material pathways: the cascade potential and cascade database of an in-use building product. IOP Conference Series: Earth and Environmental Science,

Schmidt, M. (2019). Scarcity and Environmental Impact of Mineral Resources—An Old and Never-Ending Discussion. *Resources*, *8*(1), 2. https://doi.org/10.3390/resources8010002

Schroeder, G. N., Steinmetz, C., Pereira, C. E., & Espindola, D. B. (2016). Digital Twin Data Modeling with AutomationML and a Communication Methodology for Data Exchange. *IFAC-PapersOnLine*, *49*(30), 12-17. https://doi.org/10.1016/j.ifacol.2016.11.115

Schroeder, P., Anggraeni, K., & Weber, U. (2019). The Relevance of Circular Economy Practices to the Sustainable Development Goals. *Journal of Industrial Ecology*, *23*(1), 77-95. https://doi.org/10.1111/jiec.12732

Scipioni, S., Dini, G., & Niccolini, F. (2023). Exploring circular shipbuilding: A systematic review on circular economy business models and supporting technologies. *Journal of Cleaner Production*, *422*, 138470. https://doi.org/10.1016/j.jclepro.2023.138470

Sehrawat, D., & Gill, N. S. (2020). IoT based human activity recognition system using smart sensors. *Adv. Sci. Technol. Eng. Syst. J*, *5*(4), 516-522. https://doi.org/10.25046/aj050461

Serna-Guerrero, R., Ikonen, S., Kallela, O., & Hakanen, E. (2022). Overcoming data gaps for an efficient circular economy: A case study on the battery materials ecosystem. *Journal of Cleaner Production*, *374*, 133984. https://doi.org/10.1016/j.jclepro.2022.133984

Ship Recyclers' Association of Turkey. (2024). *Our Facilities*. https://www.gemisander.com/our-facilities

Siddiqi, M. U. R., Ijomah, W. L., Dobie, G. I., Hafeez, M., Gareth Pierce, S., Ion, W., Mineo, C., & MacLeod, C. N. (2019). Low cost three-dimensional virtual model construction for remanufacturing industry. *Journal of Remanufacturing*, *9*(2), 129-139. https://doi.org/10.1007/s13243-018-0059-5

Sihvonen, S., & Ritola, T. (2015). Conceptualizing ReX for Aggregating End-of-life Strategies in Product Development. *Procedia CIRP*, *29*, 639-644. https://doi.org/10.1016/j.procir.2015.01.026

Silva, D., Garrido, J., Lekube, B., & Arrillaga, A. (2023). On-board and port 3D printing to promote a maritime plastic circular economy. *Journal of Cleaner Production*, *407*, 137151. https://doi.org/10.1016/j.jclepro.2023.137151

Singhal, D., Tripathy, S., & Jena, S. K. (2019). Acceptance of remanufactured products in the circular economy: an empirical study in India. *Management Decision*, *57*(4), 953-970. https://doi.org/10.1108/MD-06-2018-0686

Smith, T., Baresic, D., Fahnestock, J., Galbraith, C., Velandia Perico, C., Rojon, I., & Shaw, A. (2021). *A strategy for the transition to zero-emission shipping*. UMAS,. https://www.u-mas.co.uk/wp-content/uploads/2021/10/Transition-Strategy-Report.pdf

Smith, V. M., & Keoleian, G. A. (2004). The Value of Remanufactured Engines: Life-Cycle Environmental and Economic Perspectives. *Journal of Industrial Ecology*, *8*(1-2), 193-221. https://doi.org/10.1162/1088198041269463

Smol, M., Kulczycka, J., Henclik, A., Gorazda, K., & Wzorek, Z. (2015). The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. *Journal of Cleaner Production*, *95*, 45-54. https://doi.org/10.1016/j.jclepro.2015.02.051

Sohn, H. Y. (2020). Energy Consumption and CO2 Emissions in Ironmaking and Development of a Novel Flash Technology. *Metals*, *10*(1), 54. https://doi.org/10.3390/met10010054

Solakivi, T., Kiiski, T., Kuusinen, T., & Ojala, L. (2021). The European Ship Recycling Regulation and its market implications: Ship-recycling capacity and market potential. *Journal of Cleaner Production*, *294*, 126235. https://doi.org/10.1016/j.jclepro.2021.126235

Soltani, K., Bushuev, O., Tugova, E., Ghanbari, M., Henry, M. P., & Rezazadeh, G. (2020, 17-19 Nov. 2020). Modelling Fluid Loss Faults in an Industrial Pressure Sensor. 2020 Global Smart Industry Conference (GloSIC),

Souza, G. (2013). Closed-Loop Supply Chains: A Critical Review, and Future Research*. *Decision Sciences*, *44*. https://doi.org/10.1111/j.1540-5915.2012.00394.x

Souza, G. C. (2014). Closed-Loop Supply Chains with Remanufacturing. In *State-of-the-Art Decision-Making Tools in the Information-Intensive Age* (pp. 130-153). https://doi.org/10.1287/educ.1080.0040

SSI. (2021). *Exploring shipping's transition to a circular industry*. Sustainable Shipping Initiative. https://www.sustainableshipping.org/wp-content/uploads/2022/02/Ship-lifecycle-report-final.pdf

Stahel, W. R. (2010). *The performance economy* (Second edition.. ed.). Place of publication not identified : Palgrave Macmillan. https://books.google.co.uk/books?id=Oh5-DAAAQBAJ

Stahel, W. R. (2013). The business angle of a circular economy–higher competitiveness, higher resource security and material efficiency. *A new dynamic: Effective business in a circular economy*, *1*.

Steuer, B., Staudner, M., & Ramusch, R. (2021). Role and potential of the circular economy in managing end-of-life ships in China. *Resources, Conservation and Recycling*, *164*, 105039. https://doi.org/10.1016/j.resconrec.2020.105039

Stopford, M. (2009). *Maritime Economics 3e* (3 ed.). Routledge.

Sundin, E., Östlin, J., Rönnbäck, A. Ö., Lindahl, M., & Sandström, G. Ö. (2008). Remanufacturing of products used in product service system offerings. In *Manufacturing Systems and Technologies for the New Frontier* (pp. 537-542). Springer London. https://doi.org/10.1007/978-1-84800-267-8_110

Tola, F., Mosconi, E. M., Marconi, M., & Gianvincenzi, M. (2023). Perspectives for the Development of a Circular Economy Model to Promote Ship Recycling Practices in the European Context: A Systemic Literature Review. *Sustainability*, *15*(7), 5919. https://doi.org/10.3390/su15075919

Totaro, A. I. (2021). *Remanufacturing: A vast untapped potential for circularity*. Renewable Matter,. Retrieved 18/06/2024 from https://www.renewablematter.eu/en/remanufacturing-a-vast-untapped-potential-for-circularity

Tozanli, Ö., Kongar, E., & Gupta, S. M. (2020a). Evaluation of Waste Electronic Product Trade-in Strategies in Predictive Twin Disassembly Systems in the Era of Blockchain. *Sustainability*, *12*(13), 5416. https://doi.org/10.3390/su12135416

Tozanli, Ö., Kongar, E., & Gupta, S. M. (2020b). Trade-in-to-upgrade as a marketing strategy in disassembly-to-order systems at the edge of blockchain technology. *International Journal of Production Research*, *58*(23), 7183-7200. https://doi.org/10.1080/00207543.2020.1712489

Tukker, A. (2015). Product services for a resource-efficient and circular economy – a review. *Journal of Cleaner Production*, *97*, 76-91. https://doi.org/10.1016/j.jclepro.2013.11.049

Umeda, Y., Takata, S., Kimura, F., Tomiyama, T., Sutherland, J. W., Kara, S., Herrmann, C., & Duflou, J. R. (2012). Toward integrated product and process life cycle planning—An environmental perspective. *CIRP annals*, *61*(2), 681-702. https://doi.org/10.1016/j.cirp.2012.05.004

UNCTAD. (2022a). *Merchant Fleet*. Retrieved 20/02/2023 from https://hbs.unctad.org/merchant-fleet/

UNCTAD. (2022b). *Review of Maritime Transport 2022*. https://unctad.org/system/files/official-document/rmt2022_en.pdf

UNCTAD. (2023). *Review of Maritime Transport 2023*. https://unctad.org/meeting/launch-review-maritime-transport-2023

UNCTADstat. (2023). *Data Centre, Maritime Transport*. UNCTADstat. Retrieved 15/12/2023 from https://unctadstat.unctad.org

UNCTADstat. (2024, 05/06/2024). *Data Centre, Maritime Transport*. UNCTADstat. Retrieved 06/06/2024 from https://unctadstat.unctad.org/datacentre/dataviewer/US.MerchantFleet

US FDA. (2018, 09/17/2018). *Radio Frequency Identification (RFID).* Retrieved January from https://www.fda.gov/radiation-emitting-products/electromagnetic-compatibility-emc/radio-frequency-identification-rfid

Valls-Val, K., Ibáñez-Forés, V., & Bovea, M. D. (2022). How can organisations measure their level of circularity? A review of available tools. *Journal of Cleaner Production*, *354*, 131679. https://doi.org/10.1016/j.jclepro.2022.131679

Van Heerden, D.-J., & Curran, R. (2011). Value extraction from end-of-life aircraft. In R. Blockley & W. Shyy (Eds.), *Encyclopedia of Aerospace Engineering* (pp. 3715-3726). Wiley. https://doi.org/10.1002/9780470686652

van t'Hoff, P., & Hoezen, D. (2021). *Exploring shipping's transition to a circular industry*. Sustainable Shipping Initiative. https://www.sustainableshipping.org/wp-content/uploads/2022/02/Ship-lifecycle-report-final.pdf

Volvo Group. (n.d.). *Environment and Resources*. Retrieved 12/05/2024 from https://www.volvogroup.com/en/sustainable-transportation/responsible-business/resources.html

Volvo Penta. (2021a). *Volvo Penta Reman – How worn-out Volvo components are reborn as remanufactured industrial engines*. Retrieved 19/12/2021 from https://www.youtube.com/watch?v=v3-tR-Z_UxQ

Volvo Penta. (2021b). *Volvo Penta Reman Catalogue for Marine and Industrial Engines*. Retrieved 18/05/2022 from https://www.volvopenta.com/-/media/volvopenta/parts/documents/volvo-penta-reman-catalogue.pdf

Volvo Penta. (2024). *Volvo Penta Remanufacturing at sea – explained by our product managers*. Retrieved 17/07/2024 from https://www.youtube.com/watch?v=gtGuuQ0rdGQ

Volvo Penta. (n.d.-a). *Becoming world leader in sustainable power solutions*. Retrieved 12/07/2024 from https://www.volvopenta.com/about-us/news-page/2021/dec/becoming-world-leader-in-sustainable-power-solutions/

Volvo Penta. (n.d.-b). *Giving new life to old engines - Reman Engines*. Retrieved 18/06/2024 from https://www.volvopenta.com/about-us/news-page/2021/dec/giving-new-life-to-old-engines-reman-engines/

Volvo Penta. (n.d.-c). *Remanufactured Marine Engines and Components*. Retrieved 02/06/2024 from https://www.volvopenta.com/marine/parts/remanufactured-marine-engines-and-components/

Wahab, D. A., Blanco-Davis, E., Ariffin, A. K., & Wang, J. (2018). A review on the applicability of remanufacturing in extending the life cycle of marine or offshore components and structures. *Ocean Engineering*, *169*, 125-133. https://doi.org/10.1016/j.oceaneng.2018.08.046

Walden, J., Steinbrecher, A., & Marinkovic, M. (2021). Digital product passports as enabler of the circular economy. *Chemie Ingenieur Technik*, *93*(11), 1717-1727. https://doi.org/10.1002/cite.202100121

Wan, Z., Zhu, M., Chen, S., & Sperling, D. (2016). Pollution: Three steps to a green shipping industry. *Nature*, *530*(7590), 275-277. https://doi.org/10.1038/530275a

Wang, X., Li, J., Jia, X., Ma, M., & Ren, Y. (2021). Characterization of Carbonaceous Deposits on an End-of-Life Engines for Effective Cleaning for Remanufacturing. *Sustainability*, *13*(2), 950. https://doi.org/10.3390/su13020950

Wärtsilä. (2012). 2-Stroke Remanufacturing Solutions. In.

Wärtsilä. (2022). *Workshop & reconditioning center (2-stroke)*. Retrieved January from https://www.wartsila.com/services-catalogue/engine-services-2-stroke/workshop-reconditioning-center

Weiss, M., Heywood, J., Drake, E., Schafer, A., & AuYeung, F. (2000). On the Road in 2020: A Well-to-Wheels Assessment on New Passenger Car Technologies. In: Report No. EL 00-003, MIT Energy Laboratory. Cambridge, MA.

Wilde, A. S., Wanielik, F., Rolinck, M., Mennenga, M., Abraham, T., Cerdas, F., & Herrmann, C. (2022). Ontology-based approach to support life cycle engineering: Development of a data and knowledge structure. *Procedia CIRP*, *105*, 398-403. https://doi.org/10.1016/j.procir.2022.02.066

Wilts, H., & Berg, H. (2018). *The digital circular economy: Can the digital transformation pave the way for resource-efficient materials cycles?* https://epub.wupperinst.org/frontdoor/deliver/index/docId/6978/file/6978_Wilts.pdf

Yadav, S., & Singh, S. P. (2020). Blockchain critical success factors for sustainable supply chain. *Resources, Conservation and Recycling*, *152*, 104505. https://doi.org/10.1016/j.resconrec.2019.104505

Yan, R., Wang, J., & Zheng, W. G. (2013). Application and Development of Ship Welding Material. *Advanced Materials Research*, *774-776*, 1426-1429. https://doi.org/10.4028/www.scientific.net/AMR.774-776.1426

Yang, S., M. R., A. R., Kaminski, J., & Pepin, H. (2018). Opportunities for Industry 4.0 to Support Remanufacturing. *Applied Sciences*, *8*(7), 1177. https://doi.org/10.3390/app8071177

Yuan, Z., Bi, J., & Moriguichi, Y. (2006). The Circular Economy: A New Development Strategy in China. *Journal of Industrial Ecology*, *10*(1-2), 4-8. https://doi.org/10.1162/108819806775545321

Zhang, Z., Matsubae, K., & Nakajima, K. (2021). Impact of remanufacturing on the reduction of metal losses through the life cycles of vehicle engines. *Resources, Conservation and Recycling*, *170*, 105614. https://doi.org/10.1016/j.resconrec.2021.105614

Zhu, Q., Geng, Y., & Lai, K.-h. (2010). Circular economy practices among Chinese manufacturers varying in environmental-oriented supply chain cooperation and the performance implications. *Journal of Environmental Management*, *91*(6), 1324-1331. https://doi.org/10.1016/j.jenvman.2010.02.013

Zink, T., & Geyer, R. (2017). Circular Economy Rebound. *Journal of Industrial Ecology*, *21*(3), 593-602. https://doi.org/10.1111/jiec.12545

Zis, T., & Psaraftis, H. N. (2019). Operational measures to mitigate and reverse the potential modal shifts due to environmental legislation. *Maritime Policy & Management*, *46*(1), 117-132. https://doi.org/10.1080/03088839.2018.1468938

Zygiaris, S. (2018). *Database Management Systems: A Business-oriented Approach Using ORACLE, MySQL, and MS Access*. Emerald Publishing Limited.

Research Outputs

The following publications were generated throughout the timespan of the PhD studies related to this thesis:

Journal Articles:

Okumus, D., Andrews, E., & Gunbeyaz, S. A. (2024). Developing circularity metrics for the maritime industry: A stakeholder focused study. *Ocean Engineering*, *312*, 119158. https://doi.org/10.1016/j.oceaneng.2024.119158

Okumus, D., Gunbeyaz, S. A., Kurt, R. E., & Turan, O. (2024). An Approach to Advance Circular Practices in the Maritime Industry through a Database as a Bridging Solution. *Sustainability*, *16*(1), 453. https://doi.org/10.3390/su16010453

Okumus, D., Gunbeyaz, S. A., Kurt, R. E., & Turan, O. (2023). Towards a circular maritime industry: Identifying strategy and technology solutions. *Journal of Cleaner Production*, *382*, 134935. https://doi.org/10.1016/j.jclepro.2022.134935

Peer-reviewed Conference papers:

Okumus, D., Gunbeyaz, S. A., Kurt, R. E., & Turan, O. (2023). Circular economy approach in the maritime industry: Barriers and the path to sustainability. *Transportation Research Procedia*, *72*, 2157-2164. https://doi.org/10.1016/j.trpro.2023.11.701

White papers:

Okumus, D., Gunbeyaz, S. A., & Karamperidis, S. (2023). *Potential Impact of the Circular Economy Concept in Maritime Transport* (White Paper - Circular Economy Network+ in Transportation Systems. University of Warwick.

https://warwick.ac.uk/fac/sci/wmg/research/materials/smam/cents/activities/whitepapers/maritime.pdf

Research project reports:

Okumus, D., Gunbeyaz, S. A., Kurt, R. E., Turan, O., Canbulat, O., & Giagloglou, E. (2022). *Circular Economy- Increased Value Extraction from End of Life Marine Assets* (CENTS: Circular Economy Network+ in Transportation Systems, Project Report). https://pureportal.strath.ac.uk/en/projects/cents-circular-economy-network-in-transportation-systems-maritime

Abstracts presented in international conferences:

Okumus, D., & Gunbeyaz, S. A. (2024). *Enhancing maritime sustainability through circular economy metrics.* Abstract from Europe-Korea Conference on Science and Technology, Birmingham, United Kingdom. https://www.ekc2024.org/

Okumus, D., Gunbeyaz, S. A., & Karamperidis, S. (2023). *Circular economy approach in cargo ship design and onboard equipment utilisation.* Abstract from International Conference on Circular Economy in Transport (ICCET), Cranfield University, United Kingdom. https://pureportal.strath.ac.uk/en/publications/circular-economy-approach-in-cargo-ship-design-and-onboard-equipm

Okumus, D., Gunbeyaz, S. A., Kurt, R. E., & Turan, O. (2021). *Circular economy approach in the maritime industry: barriers and opportunities.* Abstract from Global Maritime Conference (GMC 2021), Istanbul, Turkey. https://pureportal.strath.ac.uk/en/publications/circular-economy-approach-in-the-maritime-industry-barriers-and-o

In addition to these publications, the author also participated in several other research projects and published the following academic work during their PhD studies:

Other Journal Articles:

Okumus, D., Fariya, S., Tamer, S., Gunbeyaz, S. A., Yildiz, G., Kurt, R. E., & Barlas, B. (2023). The impact of fatigue on shipyard welding workers' occupational health and safety and performance. *Ocean Engineering*, *285*, 115296. https://doi.org/10.1016/j.oceaneng.2023.115296

Uzun, D., **Okumus, D.,** Canbulat, O., Gunbeyaz, S. A., Karamperidis, S., Hudson, D., Turan, O., & Allan, R. (2024). Port energy demand model for implementing onshore power supply and alternative fuels. *Transportation Research Part D, 136,* 104432. https://doi.org/10.1016/j.trd.2024.104432

Tamer, S., **Okumus, D.,** Fariya, S., Ahn, S. I., Gunbeyaz, S. A., Yildiz, G., & Barlas, B. (accepted-in publication). The impact of the learning curve on the production performance of shipyard welding workers. *Ships and Offshore Structures*.

Other Book Chapters:

Karamperidis, S., **Okumus, D.,** Uzun, D., Gunbeyaz, S. A., & Turan, O. (2023). Actions by Ports to Support Green Maritime Operations: A Real Case Study—The Port of Plymouth, UK. In M. Lind, W. Lehmacher, & R. Ward (Eds.), *Maritime Decarbonization : Practical Tools, Case Studies and Decarbonization Enablers* (pp. 319-335). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-39936-7_24

Other Research project reports:

Okumus, D., Tamer, S., Fariya, S., Gunbeyaz, S. A., Yildiz, G., Kurt, R. E., Turan, O., & Barlas, B. (2022). *The effect of the learning curve on the HSE and*

efficiency. Lloyd's Register Foundation. https://pureportal.strath.ac.uk/en/projects/the-effect-of-learning-curve-on-the-hse-and-efficiency

Okumus, D., Tornaci, F., Gunbeyaz, S.A., Karamperidis, S., Turan, O., & Kurt, R. E. (2023). *Future ports and marinas: Supporting the decarbonisation transition with decision support.* Transport Research and Innovation Grants, Connected Places Catapult. https://pureportal.strath.ac.uk/en/projects/future-ports-and-marinas-supporting-the-decarbonisation-transitio-2

A. Appendix A

Q1 - Which of the following status defines your organisation the best?

Academia

Shipyard (new builds and repair)

Ship owner/operator

Original equipment manufacturer (OEM)

Classification society

Local/International Authorities

Ship recycling yards

Other (Engineering consultancy, Design office, NGO)

Q2 - Where is your organisation based?

____

Q3 - What is your experience level in the maritime industry?

____

Q4 - Have you heard about the circular economy concept?

YES / NO

Q5 - How do you rate your knowledge on Remanufacture/Repurpose/Reuse/Recycle (RRR) practices?

In general context

In the maritime industry

Rating Scale: from None to Very High.

Q6 - Are you confident that your knowledge about the Circular Economy concept is sufficient to apply it in your business?

Very confident
Confident
Not confident
Not at all confident

Q7 - What is your opinion on RRR potential of below components on board vessels?

a. Engines (Main and auxiliary)
b. Hydraulic equipment (pumps, motors, cylinders etc.)

Rating Scale: from None to Very High.

Q8 - Would you use remanufactured components on your vessels?

YES / NO / Depends on incentives

Q9 - Which of the below incentives would you consider to use remanufactured components on your vessels? Please select all that apply.

Warranty from the manufacturer
Other (please specify) _____
Legislative
Financial (e.g. tax rebate if using remanufactured items)
Cheaper than new equipment
After-purchase support from the manufacturer

Q10 - Would you prefer a remanufactured component if it offers (or guaranteed with) the same reliability and quality as a brand new one? (Considering its price, sustainability and environmental advantages)

Yes / No

Q11 - You mentioned you do not prefer using RRR components on your vessel, which of the below applies the best for you?

Reliability concerns
Legislative barriers/difficulties
RRR components would not perform as good as the brand new equipment
No real benefit in terms of economics
Other (please specify) _______

Q12 - Would change your mind if RRR components offer: Please select all that apply.

- The same warranty conditions as brand new products from the manufacturer
- Significant price advantage
- Classification society approval
- Other (please specify) __________

Q13 - What is the current demand for engines (ME/Aux) and hydraulic components on the second hand/used market?

a. Engines (Main and auxiliary)
b. Hydraulic equipment (pumps, motors, cylinders etc.)

Q14 - Do you think it would worth remanufacturing/reconditioning efforts or do you think that the used market is advantageous as it is?

Complete engine
Engine block
Cylinder heads
Crankshaft
Aftercooler/intercooler
Turbochargers
Hydraulic pumps/motors
Hydraulic cylinders and other hydraulic components

Q15 - Do you sell below components as scrap metals or as used/second hand products or spare parts?

Complete engine
Engine block
Cylinder heads
Crankshaft
Aftercooler/intercooler
Turbochargers
Hydraulic pumps/motors
Hydraulic cylinders and other hydraulic components

Q16 - Which of the following practices do you currently do? Please select all that apply.

- o Reuse
- o Refurbish
- o Recycle
- o Redesign products to reduce waste
- o Provide a product as a service
- o Remanufacture
- o Seek to reduce waste through procurement
- o Work with your supply chain to manage out waste

- Use waste heat

Q17 - Are you able to remanufacture/repurpose/refit engines and/or hydraulic components?

Yes / No

Q18 - Do you prefer to remanufacture/repurpose/refit engines and/or hydraulic components?

Definitely not
Probably not
Might or might not
Probably yes
Definitely yes

Q19 - How do you rate repurposing* options for engines and hydraulic components on board ships?

*** Repurposing components after decommissioning for other industries**

Aux machinery, Gen-sets
Hydraulic pumps and motors
Main engine
Cylinders and other hydraulic equipment

Q20 - Which other industries would benefit from remanufactured/repurposed components such as engines and pumps in your opinion?

____

Q21 - What do you think about Remanufacture hub/parks, which aim to achieve economy of scale and lower transportation costs for remanufacturing operations. Would you participate in such a business model?

Definitely not
Probably not
Might or might not
Probably yes
Definitely yes

Q22 - Would you cooperate with third-party remanufacturing companies if;

a- You provide original parts and
b- You inspect finished products and conduct certification studies ?

Definitely not
Probably not
Might or might not
Probably yes
Definitely yes

Q23 - Would you approve RRR components on vessels (provided valid OEM product certifications) ?

YES / NO / Requires further study

Q24 - What should be done for remanufactured components to be approved by classification societies? Please select all that apply.

- OEM warranty & certification
- Third-party product quality tests
- Other (please specify) ________

Q25 - If owner-OEM-class approves RRR components, what would you consider about providing regulation-wise support for remanufactured components? (e.g. extending NOx SOx emissions deadline for ships with remanufactured engines)

Rating Scale: from Not possible at all to Definitely could provide some support.

Q26 - Would you consider a financial incentive program encouraging RRR ? (e.g. tax support from local authorities)

YES / NO / Already providing financial incentives

Q27 - Is there any plans for a research/study the circular economy in the maritime industry in the near future?

Definitely not
Probably not
Might or might not
Probably yes
Definitely yes

Q28 - What is your estimation on savings comparing a remanufactured engine/component and brand new one, considering satisfactory quality core parts (such as engine block) provided?

0 to 20%
20% to 40%
40% to 60%
More than 60%

Q29 - Do you have any on-going studies focused on design-for-remanufacturing for new products?

YES / NO

Q30 - If you have any on-going studies focused on design for remanufacturing for new products, can you share the details of your project?

YES / NO

Q31 - What are the challenges on providing core parts for RRR purposes? Please select all that apply.

- o Know-how gap
- o Limited workforce
- o Demand from the market
- o Lack of opportunity to market these goods
- o Regulatory barriers
- o Other (please specify) ______

Q32 - Where do you think Circular Economy opportunities could lie in the maritime industry? Please select all that apply.

- o Reuse/refurbishment/recycling
- o Different raw materials
- o Product or service design
- o Procurement
- o Supply chain
- o Business process change
- o None at the moment
- o Other (please specify) _______

Q33 - Would you be interested to be contacted regarding this project in the near future?

YES / NO

Q34 - Your name: __________

Q35 - Your email address: ____________

B. Appendix B

- Query 1:

SELECT OEMs.[OEM Name], [Component Specs].[Model Name], Components.[Component Type], Components.[Serial Number], Components.[Acquired Date], Components.Condition, Components.[Approx EoL Value], Vessels.[IMO Number], Vessels.[Vessel Name], Owners.Company, Vessels.[Recycled Vessel], Components.[Recycled Component]

FROM Owners INNER JOIN (Vessels INNER JOIN (OEMs INNER JOIN ([Component Specs] INNER JOIN Components ON [Component Specs].[Model ID] = Components.[Equipment Model ID]) ON OEMs.[OEM ID] = [Component Specs].[OEM ID]) ON Vessels.[Vessel ID] = Components.[Ship ID]) ON Owners.[Owner ID] = Vessels.[Owner ID]

WHERE (((Owners.Company)="Ship Owner C"));

- Query 2:

SELECT Owners.Company, Vessels.[Vessel Name], Vessels.[IMO Number], Vessels.GT, Vessels.DWT, Vessels.[Built Date], [Building Shipyard].[Shipyard Name], [Repairing Shipyard].[Shipyard Name], Recyclers.[Company Name], Vessels.[Estimated EoL Date], Vessels.Notes

FROM Owners INNER JOIN (Recyclers INNER JOIN (Shipyards AS [Repairing Shipyard] INNER JOIN (Shipyards AS [Building Shipyard] INNER JOIN Vessels ON [Building Shipyard].[Shipyard ID] = Vessels.[Building Shipyard ID]) ON [Repairing Shipyard].[Shipyard ID] = Vessels.[Repairing Shipyard ID]) ON Recyclers.[Recycling Facility ID] = Vessels.[Recycler ID]) ON Owners.[Owner ID] = Vessels.[Owner ID]

WHERE (((Owners.Company)="Ship Owner C"));

- Query 3:

SELECT Vessels.[Vessel Name], Vessels.[IMO Number], [Building Shipyards].[Shipyard Name], [Repairing Shipyards].[Shipyard Name], Components.[Component Type], Components.[Serial Number], Components.[Acquired Date], Components.Condition, Components.[Approx EoL Value], OEMs.[OEM Name], [Component Specs].[Model Name], [Component Specs].[Max Height (m)], [Component Specs].[Max Width (m)], [Component Specs].[Max Length (m)], [Component Specs].[Dry Weight (kg)]

FROM Owners INNER JOIN (Shipyards AS [Building Shipyards] INNER JOIN (Shipyards AS [Repairing Shipyards] INNER JOIN (OEMs INNER JOIN ([Component Specs] INNER JOIN (Vessels INNER JOIN Components ON Vessels.[Vessel ID] = Components.[Ship ID]) ON [Component Specs].[Model ID] = Components.[Equipment Model ID]) ON OEMs.[OEM ID] = [Component Specs].[OEM ID]) ON [Repairing Shipyards].[Shipyard ID] = Vessels.[Repairing Shipyard ID]) ON [Building Shipyards].[Shipyard ID] = Vessels.[Building Shipyard ID]) ON Owners.[Owner ID] = Vessels.[Owner ID]

WHERE (((Owners.Company)="Ship Owner C"))

ORDER BY Vessels.[Vessel Name], Components.[Component Type];

- Query 4:

SELECT [Building Shipyards].[Shipyard Name], Vessels.[Vessel Type], Vessels.[Vessel Name], Vessels.[IMO Number], Vessels.GT, Vessels.DWT, Components.[Component Type], OEMs.[OEM Name], [Component Specs].[Model Name], Components.[Serial Number]

FROM OEMs INNER JOIN ([Component Specs] INNER JOIN (Shipyards AS [Building Shipyards] INNER JOIN (Vessels INNER JOIN Components ON Vessels.[Vessel ID] = Components.[Ship ID]) ON [Building Shipyards].[Shipyard ID] = Vessels.[Building Shipyard ID]) ON [Component Specs].[Model ID] =

Components.[Equipment Model ID]) ON OEMs.[OEM ID] = [Component Specs].[OEM ID]

WHERE ((([Building Shipyards].[Shipyard Name])="Shipyard A"))

ORDER BY Vessels.[Vessel Name], Components.[Component Type];

- Query 5:

SELECT [Repairing Shipyard].[Shipyard Name], Vessels.[Vessel Name], Vessels.[Vessel Type], Vessels.DWT, Vessels.GT, Owners.Company, Owners.[Contact Name], Owners.[Mobile Phone], Owners.[E-mail address], [Building Shipyard].[Shipyard Name], [Building Shipyard].[Contact Name], [Building Shipyard].[E-mail address], [Building Shipyard].[Mobile Phone]

FROM Shipyards AS [Building Shipyard] INNER JOIN (Shipyards AS [Repairing Shipyard] INNER JOIN (Owners INNER JOIN Vessels ON Owners.[Owner ID] = Vessels.[Owner ID]) ON [Repairing Shipyard].[Shipyard ID] = Vessels.[Repairing Shipyard ID]) ON [Building Shipyard].[Shipyard ID] = Vessels.[Building Shipyard ID]

WHERE ((([Repairing Shipyard].[Shipyard Name])="Shipyard C"))

ORDER BY Vessels.[Vessel Name];

- Query 6:

SELECT [Repairing Shipyard].[Shipyard Name], Vessels.[Vessel Name], Components.[Component Type], OEMs.[OEM Name], [Component Specs].[Model Name], [Component Specs].[Max Height (m)], [Component Specs].[Max Width (m)], [Component Specs].[Max Length (m)], [Component Specs].[Dry Weight (kg)], Components.[Serial Number], Components.[Acquired Date], Components.Condition, Components.[Approx EoL Value], Components.[Recycled Component], Components.Notes

FROM OEMs INNER JOIN ([Component Specs] INNER JOIN ((Shipyards AS [Repairing Shipyard] INNER JOIN Vessels ON [Repairing Shipyard].[Shipyard ID] = Vessels.[Repairing Shipyard ID]) INNER JOIN Components ON Vessels.[Vessel ID] = Components.[Ship ID]) ON [Component Specs].[Model ID] = Components.[Equipment Model ID]) ON OEMs.[OEM ID] = [Component Specs].[OEM ID]

WHERE ((([Repairing Shipyard].[Shipyard Name])="Shipyard C"))

ORDER BY Vessels.[Vessel Name], Components.[Component Type];

- Query 7:

SELECT Recyclers.[Company Name], Vessels.[Vessel Name], Vessels.[IMO Number], Vessels.[Vessel Type], Vessels.GT, Vessels.DWT, Vessels.[Built Date], Owners.Company, Owners.[Contact Name], Owners.[E-mail address], Owners.[Mobile Phone], Vessels.Notes

FROM Owners INNER JOIN (Recyclers INNER JOIN Vessels ON Recyclers.[Recycling Facility ID] = Vessels.[Recycler ID]) ON Owners.[Owner ID] = Vessels.[Owner ID]

WHERE (((Recyclers.[Company Name])="Recycling Facility B"))

ORDER BY Vessels.[Vessel Name];

- Query 8:

SELECT Recyclers.[Company Name], Vessels.[Vessel Name], Components.[Component Type], OEMs.[OEM Name], [Component Specs].[Model Name], [Component Specs].[Max Height (m)], [Component Specs].[Max Width (m)], [Component Specs].[Max Length (m)], [Component Specs].[Dry Weight (kg)], Components.[Serial Number], Components.[Acquired Date], Components.Condition, [Component Specs].[Engine Power (kW)], [Component Specs].[Engine Displacement

(L)], [Component Specs].[Engine Speed (rpm)], [Component Specs].[Engine Emission Level], [Component Specs].Notes

FROM OEMs INNER JOIN ([Component Specs] INNER JOIN ((Recyclers INNER JOIN Vessels ON Recyclers.[Recycling Facility ID] = Vessels.[Recycler ID]) INNER JOIN Components ON Vessels.[Vessel ID] = Components.[Ship ID]) ON [Component Specs].[Model ID] = Components.[Equipment Model ID]) ON OEMs.[OEM ID] = [Component Specs].[OEM ID]

WHERE (((Recyclers.[Company Name])="Recycling Facility B") AND ((Components.[Component Type])<>"PUMP"))

ORDER BY Vessels.[Vessel Name];

- Query 9:

SELECT Recyclers.[Company Name], Vessels.[Vessel Name], Components.[Component Type], OEMs.[OEM Name], [Component Specs].[Model Name], [Component Specs].[Max Height (m)], [Component Specs].[Max Width (m)], [Component Specs].[Max Length (m)], [Component Specs].[Dry Weight (kg)], Components.[Serial Number], Components.[Acquired Date], Components.Condition, [Component Specs].[Pump Type], [Component Specs].[Pump Capacity (m3/h)], [Component Specs].[Pump Installed Power (kW)], [Component Specs].Notes

FROM OEMs INNER JOIN ([Component Specs] INNER JOIN ((Recyclers INNER JOIN Vessels ON Recyclers.[Recycling Facility ID] = Vessels.[Recycler ID]) INNER JOIN Components ON Vessels.[Vessel ID] = Components.[Ship ID]) ON [Component Specs].[Model ID] = Components.[Equipment Model ID]) ON OEMs.[OEM ID] = [Component Specs].[OEM ID]

WHERE (((Recyclers.[Company Name])=" Recycling Facility B ") AND ((Components.[Component Type])="PUMP"))

ORDER BY Vessels.[Vessel Name];

- Query 10:

SELECT OEMs.[OEM Name], [Component Specs].[Model Name], Components.[Serial Number], Vessels.[Vessel Name], Vessels.[Vessel Type], Components.[Component Type], Vessels.[Estimated EoL Date], Owners.Company, Owners.[Contact Name], Owners.[E-mail address], Owners.[Mobile Phone], Recyclers.[Company Name], Recyclers.[Contact Name], Recyclers.[E-mail address], Recyclers.[Mobile Phone]

FROM OEMs INNER JOIN ([Component Specs] INNER JOIN (Recyclers INNER JOIN (Owners INNER JOIN (Vessels INNER JOIN Components ON Vessels.[Vessel ID] = Components.[Ship ID]) ON Owners.[Owner ID] = Vessels.[Owner ID]) ON Recyclers.[Recycling Facility ID] = Vessels.[Recycler ID]) ON [Component Specs].[Model ID] = Components.[Equipment Model ID]) ON OEMs.[OEM ID] = [Component Specs].[OEM ID]

WHERE (((OEMs.[OEM Name])="Caterpillar Inc"))

ORDER BY [Component Specs].[Model Name], Vessels.[Vessel Name];

- Query 11:

SELECT Recyclers.[Company Name], Vessels.[Vessel Name], Components.[Component Type], OEMs.[OEM Name], [Component Specs].[Model Name], [Component Specs].[Dry Weight (kg)], [Component Material Breakdown].[Ferrous metals (kg)], [Component Material Breakdown].[Nonferrous metals (kg)], [Component Material Breakdown].[Alloys (kg)], [Component Material Breakdown].[Hazardous Materials (kg)], [Component Material Breakdown].[Others (kg)]

FROM ((OEMs INNER JOIN [Component Specs] ON OEMs.[OEM ID] = [Component Specs].[OEM ID]) LEFT JOIN [Component Material Breakdown] ON [Component Specs].[Model ID] = [Component Material Breakdown].[Equipment Model ID]) INNER JOIN ((Recyclers INNER JOIN Vessels ON Recyclers.[Recycling Facility ID] = Vessels.[Recycler ID]) INNER JOIN Components ON Vessels.[Vessel

ID] = Components.[Ship ID]) ON [Component Specs].[Model ID] = Components.[Equipment Model ID]

WHERE (((Recyclers.[Company Name])="Recycling Facility B") AND ((Components.[Component Type])<>"PUMP"))

ORDER BY Vessels.[Vessel Name];

- Validation workshop participants:

	Maritime Industry Experience	***Background***	***Current Stakeholder Group***
Expert 1	16 years	Naval architect, senior design engineer. Experienced in cargo vessel design. Has worked at shipyards, and ship design offices during their career.	Shipyard (new building)
Expert 2	9 years	Naval architect, has worked at shipyards as structural engineer and quality assurance engineer.	Shipyard (new building and repair)
Expert 3	17 years	Senior mechanical engineer specialised in outfitting and production. Has intensive shipyard experience.	Shipyard (new building and repair)
Expert 4	23 years	Captain by training. Currently working for a ship owner/operator company as their fleet manager. First 10 years of their experience is sailing onboard.	Ship Owner / Operator
Expert 5	32 years	Ship owner. Has a fleet of 7 vessels including general cargo and dry bulk carriers.	Ship Owner / Operator
Expert 6	14 years	Marine operations manager. Marine engineer by training. Currently oversees day-to-day operations of a shipping company with 22 vessels.	Ship Owner / Operator
Expert 7	9 years	Mechanical engineer by training, has significant experience in two different maritime OEMs. First, the manufacturer of fluid separation and treatment products. Second, an engine manufacturer.	OEM
Expert 8	13 years	Naval architect by training, has worked for one of the biggest engine manufacturers in the industry. An expert on marine engines.	OEM
Expert 9	21 years	Naval architect by training, has worked at an OEMs engine manufacturing plant for years. Currently works as a product manager and is responsible for certain types of engines in EAME region.	OEM

Expert 10	12 years	Mechanical engineering technician by training, currently works as a shipbreaking manager.	Recycling Facility
Expert 11	7 years	Mechanical engineer by training. Has worked as a health and safety engineer in shipyards and ship recycling facilities.	Recycling Facility
Expert 12	13 years	Marine engineer by training. Has been working as a shipbreaking engineer for 8 years. Had sailed during the first five years of their career.	Recycling Facility

C. Appendix C

The scoring tables in this appendix aim to convert the qualitative attributes of circular economy elements into measurable metrics. This approach is necessary due to the nature of some aspects of the circular economy, such as modularity, restoration quality, and process flows, which do not lend themselves to direct computation or tangible outputs. A number of existing circularity metrics in the literature, including the most popular ones such as Circulytics and MCI, also involve qualitative self-assessments (Patti, 2023) to reach quantitative outputs (Saidani et al., 2017).

In the development of these scoring systems, we considered various scaling options, including binary, numerical, and descriptive scales. While binary scales were considered too simplistic, purely numerical scales were found to lack the required context to effectively eliminate subjectivity. As a result, a hybrid approach was embraced, combining numerical values with descriptive criteria to establish a clear and industry-relevant definition for each score.

The scoring tables employ a multi-level scale, recommending a minimum of three levels to effectively encompass the range of performance. This study provides examples with three, four, and five levels to demonstrate how the framework can adapt to various metrics without adding unnecessary complexity.

The definitions and scoring criteria for each level are based on extensive industry engagement workshops and the authors' expertise in the maritime sector. These workshops facilitated the initial development of the scoring criteria, which were then refined and validated through subsequent metric validation interviews with industry professionals. Insights from these sessions played a crucial role in finalising the scales.

Each level's score ranges from 0 to 1, aligning with the rest of the metrics in the framework for consistency. This scoring system allows for a qualitative understanding through descriptive elements and facilitates quantitative analysis by translating these elements into numerical values.

Tables from Table C-1 to Table C-6 offer predefined scales for different circularity metrics relevant to maritime stakeholders. These scales have undergone rigorous development and validation to function as a dependable tool for evaluating circular economy practices in the maritime industry.

Table C-1: Engine room modularity metric example factors for SD-CM 2.

Levels	Definition	SD-CM 2 score
1 – Low	• No upgradability: All engine room equipment meet the required standards, however without any consideration for upgradability. • Invasive removal: Removing engines and heavy equipment involves extensive cutting and alterations, impacting superstructure. • Little remanufacturability: Only a limited number of components may have remanufacturing options, mainly by their OEMs. • Negligible transferability: There is little to no potential for transferring equipment to other vessels or industries.	0.20
2 - Basic	• Limited upgradability: All equipment in the engine room meet basic standards without a significant focus on upgradability. • Challenging removal: Removing heavy equipment and engines may require cutting or alterations, potentially affecting the superstructure. • Limited remanufacturability: Only a few critical components may be remanufacturable, primarily by their OEMs. • Minimal transferability: Transferability of equipment to other vessels and applications is limited.	0.40
3 - Moderate	• Basic upgradability: All engine room equipment complies with the latest standards and a majority of them have a potential for limited product upgrades. • Removal with considerations: Some equipment and engines can be removed with attention to minimising impact on surrounding structures. • Limited remanufacturability: Selected components in the engine room may be remanufacturable, either by their OEMs or 3rd party remanufacturers. • Limited transferability: Limited potential for transferring some equipment to other vessels or applications.	0.60
4 - Advanced	• Significant upgradability: Engine room equipment meets the latest standards and a significant portion can be upgraded to meet future standards. • Non-invasive removal: Most engines and other equipment can be removed with minimal impact on the hull and structure, avoiding extensive cutting or alteration of decks and superstructure. • Partial remanufacturability: A substantial number of critical components in the engine room are remanufacturable, either by their OEMs or 3rd party remanufacturers. • Partial transferability: Some equipment demonstrates the potential for transferability to other vessels or relevant applications.	0.80
5 - Exemplary	• Comprehensive upgradability: All equipment in the engine room adheres to the latest industry standards, and demonstrates a high degree of upgradability for future compliance. • Non-invasive removal: Engines and other heavy equipment can be removed without cutting decks above and without adversely affecting the superstructure. • Remanufacturability excellence: All equipment in the engine room is remanufacturable, either by their OEMs or by 3rd party remanufacturers. • Transferability across assets: Most of the equipment is transferable to other vessels or applications where applicable.	1

Table C-2: A predefined scale for an example onboard marine engine modularity score for OEM-CM 3.

Levels	Definition	SD-CM 2 score
1 – Basic	• Below standards compliance: Limited compliance with the latest industry standards, and quite limited upgradability options. • Challenging component replacement: Replacing individual components involves challenges and may require extensive disassembly. Maintenance processes may be complex. • Minimal remanufacturability: Limited consideration for remanufacturing. Circular economy principles are not properly integrated.	0.33
2 - Moderate	• Basic standards compliance: Engines fundamentally comply with industry standards or provide a foundation to upgrade to the industry standard. • Limited component replacement: Some key components can be replaced individually, introducing modularity in specific areas. • Balances modularity with complexity. • Initiating remanufacturability: Integrates remanufacturability practices for key components and embarks the circular economy journey for valuable parts.	0.67
3 - Advanced	• Comprehensive standards adherence: Engine and its major components adhere to the latest industry standards. Ensures a foundation for upgradability for future compliance. • Selective component replacement: Certain components can be replaced individually, streamlining maintenance and repair. • Balances modularity with operational efficiency. • Significant remanufacturability: Key components are designed for remanufacturability, extending the lifecycle. Entire unit is designed to be remanufactured multiple times.	1.00

Table C-3: Marine engine remanufacturing quality scale for OEM-CM 5.

Quality Levels	Definition	OEM-CM 5 score
1 – Basic	• Limited warranty coverage for parts only. • Warranty may not cover all parts and workmanship faults. • Limited upgradability and future compliance with regulations. • Visible cosmetic differences compared to brand-new engines. • Some performance variations compared to brand-new alternatives.	0.20
2 – Standard	• Moderate warranty coverage for parts and labour. • Warranty covers most parts and workmanship faults. • Limited options for extended warranty. • Limited upgradability to meet future standards. • Minor cosmetic differences compared to brand-new engines. • Comparable performance and technical details versus brand-new alternatives.	0.40
3 – Above-average	• Comprehensive warranty coverage for all parts and labour. • Warranty covers entire unit including workmanship faults. • Options available for extended warranty purchase. • Some upgradability to meet future standards. • Minimal cosmetic differences compared to brand-new engines. • Brand-new performance and technical details.	0.60
4 - High	• The same warranty coverage as brand-new engines, with options for extended warranty. • Warranty includes extended coverage for all parts and workmanship faults. • Engine can be remanufactured at least one more time at its end-of-life. • Significant upgradability to meet future standards. • Near-identical cosmetic appearance to brand-new engines. • Equal performance and technical specifications.	0.80

5 - Exemplary	• Warranty coverage is better than brand-new engines. Longer warranty duration is provided by default. • Warranty covers all parts and workmanship faults. • Engine can be remanufactured multiple times throughout its lifecycle. • Fully upgradable to meet future standards and regulations. • No visual difference in appearance compared to brand-new engines. • Engine performance, power, fuel consumption and all technical details are on par with brand-new alternatives.	1

Table C-4: Circular marketing practices scale for OEM-CM 8.

Marketing Levels	Definition	OEM-CM 8 score
1 – Limited	• Minimal or no communication regarding CE practices and products. • Little to no presence in advertising, labelling, certification, or reporting. • Low awareness and recognition of CE initiatives by the OEM. • Absence of promotion or integration of product service solutions (PSS) or take-back strategies at EoL stage.	0.25
2 – Basic	• Some communication regarding CE practices and products. • Moderate presence in advertising, labelling, certification, or reporting. • Efforts to raise awareness and recognition of circular economy initiatives are moderate. • Limited application of PSS or take-back strategies at product EoL, but without effective marketing and promotion.	0.50
3 – Moderate	• Clear and consistent communication regarding circular economy practices and products. • Strong presence in advertising, labelling, certification, or reporting. • Proactive efforts to raise awareness and recognition of circular economy initiatives. • Promotion and integration of PSS or take-back strategies at product end-of-life are moderate. • Limited promotion of proactive maintenance and smart recovery decision-making (SRDM) practices.	0.75
4 - Comprehensive	• Comprehensive and innovative communication regarding circular economy practices and products. • Dominant presence in advertising, labelling, certification, or reporting. • Proactive efforts to raise awareness and recognition of circular economy initiatives. • Promotion and integration of PSS or take-back strategies at product end-of-life are comprehensive. • Promotion and integration of proactive maintenance and smart recovery decision-making practices.	1.00

Table C-5: A predefined example scale for remanufactured marine components for CS-CM 1.

Levels	Definition	CS-CM 1 score
1 – Absence of Guidelines	• No specific rules, standards, or regulations regarding the use of remanufactured components. • Existing classification society guidelines do not include any mention of remanufactured components. • No promotion or encouragement of circularity in shipbuilding and maintenance through remanufactured components and equipment.	0.00
2 -Basic Guidelines	• Some initial rules, standards, or regulations regarding the use of remanufactured components may be present, but they are limited in scope or specificity. • Classification society guidelines may include limited reference to remanufactured components. • Limited promotion or encouragement of circularity in shipbuilding and maintenance through remanufactured components and equipment.	0.50
3 – Comprehensive Guidelines	• Clear and comprehensive rules, standards, or regulations regarding the use of remanufactured components are established. • Classification society guidelines explicitly include guidelines for the use of remanufactured components. • Proactive promotion and encouragement of circularity in shipbuilding and maintenance through remanufactured components and equipment.	1.00

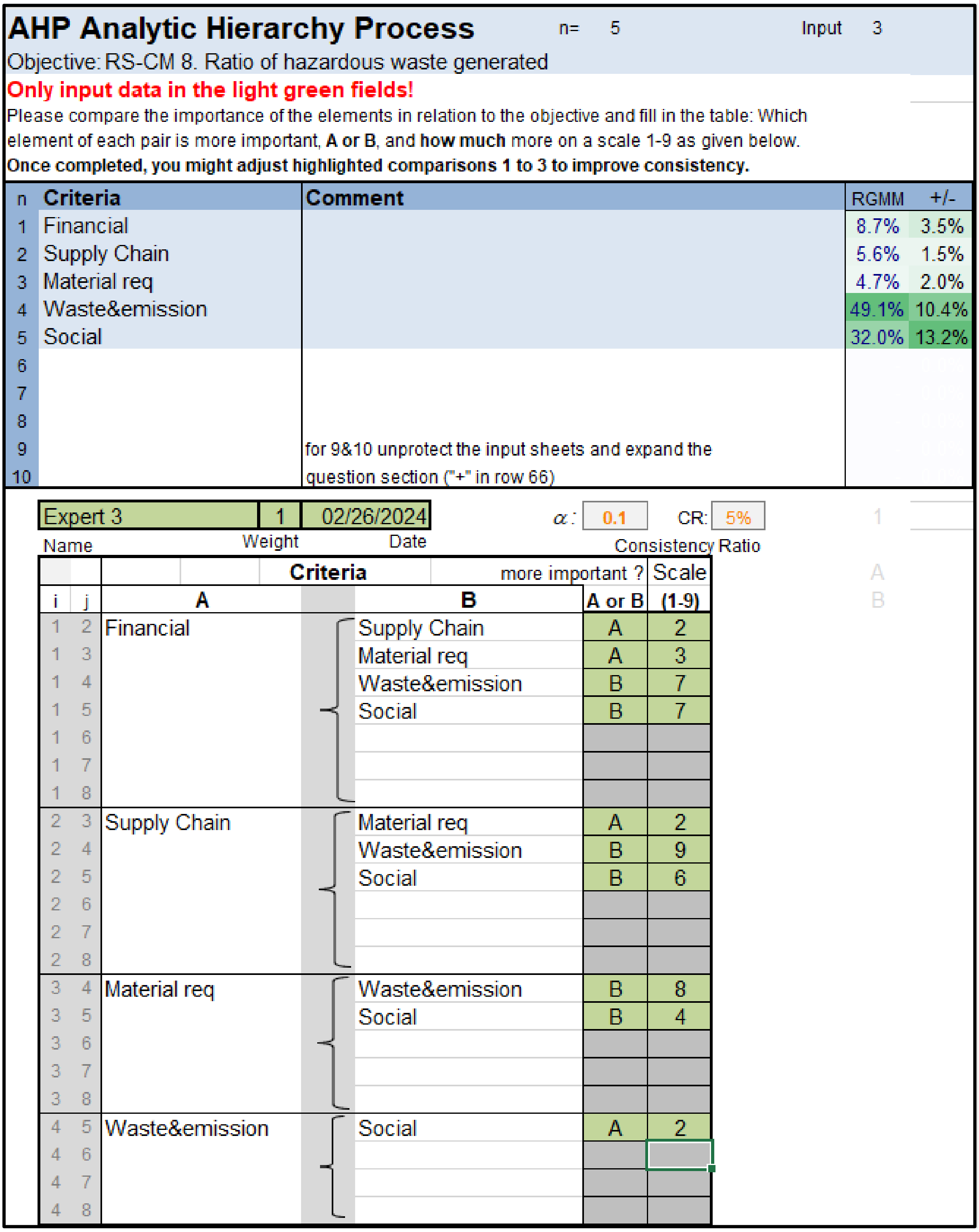
Table C-6: A predefined example scale for CS-CM 3 - certifying process for circular products.

Levels	Definition	CS-CM 3 score
1 – Absence of Certification Process	• No specific standard process for certifying circular products exists within the classification society. • Circular products are not subject to any distinct certification process compared to traditional products. • No formal requirements or guidelines for certification of circular marine equipment are established.	0.00
2 -Basic Certification Process	• Circular product certification currently involves a few preliminary steps or procedures, but their reach and level of specificity are restricted. • Circular marine equipment certification may be subject to fundamental rules or specifications set by the classification society. • Only limited distinction or formal recognition of circular products within the certification process.	0.50
3 – Comprehensive Certification Process	• A straightforward and comprehensive standard process for certifying circular products is established by the classification society. • Detailed guidelines and requirements for certifying circular marine equipment are provided. • Clear identification and official acknowledgement of circular products during the certification procedure.	1.00

Table C-7: Summary of circularity metrics for maritime stakeholders.

Total Circularity Metrics Table					
#	**Indicator Name**	**Stakeholder group**	**Indicator definition**	**Unit**	**Range**
1	SD-CM 1	Ship designers	Durability and longevity of design	%	[0, 1]
2	SD-CM 2	Ship designers	Modularity of design	Pre-defined scale	[0, 1]
3	SD-CM 3	Ship designers	Recycled-reused material weight	%	[0, 1]
4	SD-CM 4	Ship designers	RRR content in design	%	[0, 1]
5	SD-CM 5	Ship designers	Customers provided circular designs	%	[0, 1]
6	OEM-CM 1	OEMs	RRR content in products	%	[0, 1]
7	OEM-CM 2	OEMs	Durability and longevity of products	%	[0, ∞]
8	OEM-CM 3	OEMs	Modularity of products	Pre-defined scale	[0, 1]
9	OEM-CM 4	OEMs	Lead time of RRR products	%	[0, ∞]
10	OEM-CM 5	OEMs	Quality of RRR products	Pre-defined scale	[0, 1]
11	OEM-CM 6	OEMs	GHG emission reduction due to CE	%	[0, 1]
12	OEM-CM 7	OEMs	Recovered waste due to CE	%	[0, 1]
13	OEM-CM 8	OEMs	Circular marketing practices	Pre-defined scale	[0, 1]
14	OEM-CM 9	OEMs	Hazardous waste generation	%	[0, 1]
15	OEM-CM 10	OEMs	Revenue generated by circular practices	%	[0, 1]
16	BS-CM 1	Building Shipyards	Modularity of vessels built	Pre-defined scale	[0, 1]
17	BS-CM 2	Building Shipyards	Recycled-reused material weight	%	[0, 1]
18	BS-CM 3	Building Shipyards	Usage of RRR parts and equipment	%	[0, 1]
19	BS-CM 4	Building Shipyards	Durability and longevity of vessels built	%	[0, 1]
20	BS-CM 5	Building Shipyards	Customers ordered circular vessels	%	[0, 1]
21	BS-CM 6	Building Shipyards	Hazardous waste generation	%	[0, 1]
22	BS-CM 7	Building Shipyards	GHG emission reduction due to CE	%	[0, 1]
23	RS-CM 1	Repair Shipyards	Lead time of RRR spare parts	%	[0, ∞]
24	RS-CM 2	Repair Shipyards	Reused parts in repairs	%	[0, 1]
25	RS-CM 3	Repair Shipyards	Reused parts in maintenance operations	%	[0, 1]
26	RS-CM 4	Repair Shipyards	Reverse supply chain - Volume of returned cores	%	[0, 1]
27	RS-CM 5	Repair Shipyards	Reverse supply chain - Quality of returned cores	%	[0, 1]
28	RS-CM 6	Repair Shipyards	Revenue generated by circular practices	%	[0, 1]
29	RS-CM 7	Repair Shipyards	Customers provided circular parts or components	%	[0, 1]
30	RS-CM 8	Repair Shipyards	Hazardous waste generation	%	[0, 1]
31	RS-CM 9	Repair Shipyards	GHG emission reduction due to CE	%	[0, 1]
32	CS-CM 1	Classification Societies	Rules regarding remanufactured components	Pre-defined scale	[0, 1]
33	CS-CM 2	Classification Societies	Rules regarding refurbished equipment	Pre-defined scale	[0, 1]
34	CS-CM 3	Classification Societies	Standard certification process for circular products	Pre-defined scale	[0, 1]
35	CS-CM 4	Classification Societies	Type-approval tests for circular products	%	[0, 1]
36	CS-CM 5	Classification Societies	Promoting the reverse supply chain	Pre-defined scale	[0, 1]
37	OO-CM 1	Ship Owner or Operators	Longevity of their fleet	%	[0, ∞]

38	OO-CM 2	Ship Owner or Operators	Usage of RRR parts and equipment	%	[0, 1]
39	OO-CM 3	Ship Owner or Operators	Recycled-reused material weight	%	[0, 1]
40	OO-CM 4	Ship Owner or Operators	Reverse supply chain - Volume of returned cores	%	[0, 1]
41	OO-CM 5	Ship Owner or Operators	Reverse supply chain - Quality of returned cores	%	[0, 1]
42	OO-CM 6	Ship Owner or Operators	Solid waste generation during EoL	%	[0, 1]
43	OO-CM 7	Ship Owner or Operators	Hazardous waste generation during EoL	%	[0, 1]
44	OO-CM 8	Ship Owner or Operators	Solid waste generation during repair or refit	%	[0, 1]
45	OO-CM 9	Ship Owner or Operators	Hazardous waste generation during repair or refit	%	[0, 1]
46	RF-CM 1	Recycling Facilities	Revenue generated by circular practices	%	[0, 1]
47	RF-CM 2	Recycling Facilities	Value retention due to RRR	%	[0, 1]
48	RF-CM 3	Recycling Facilities	GHG emission reduction due to CE	%	[0, 1]
49	RF-CM 4	Recycling Facilities	Solid waste generation during EoL	%	[0, 1]
50	RF-CM 5	Recycling Facilities	Waste reduction due to CE principles	%	[0, 1]
51	RF-CM 6	Recycling Facilities	Hazardous waste generation	%	[0, 1]
52	RF-CM 7	Recycling Facilities	Reverse supply chain - Volume of returned cores	%	[0, 1]
53	RF-CM 8	Recycling Facilities	Reverse supply chain - Quality of returned cores	%	[0, 1]
54	CO-CM 1	Cargo Owners	Circular cargo transportation ratio	%	[0, 1]
55	CO-CM 2	Cargo Owners	Circular packaging indicator	%	[0, 1]
56	AUT-CM 1	Authorities (Local or Int)	Regulations regarding remanufactured equipment	Yes-or-no scale	[0, 1]
57	AUT-CM 2	Authorities (Local or Int)	Regulations regarding refurbished products	Yes-or-no scale	[0, 1]
58	AUT-CM 3	Authorities (Local or Int)	Promoting the circular practices - incentives	Yes-or-no scale	[0, 1]
59	AUT-CM 4	Authorities (Local or Int)	Defining a circular vessel	Yes-or-no scale	[0, 1]



AHP Analytic Hierarchy Process

n= 5 Input 3

Objective: RS-CM 8. Ratio of hazardous waste generated

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM	+/-
1	Financial		8.7%	3.5%
2	Supply Chain		5.6%	1.5%
3	Material req		4.7%	2.0%
4	Waste&emission		49.1%	10.4%
5	Social		32.0%	13.2%
6				
7				
8				
9		for 9&10 unprotect the input sheets and expand the		
10		question section ("+" in row 66)		

Expert 3 | 1 | 02/26/2024 — α: 0.1 — CR: 5%

Name | Weight | Date — Consistency Ratio

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Financial	Supply Chain	A	2
1	3		Material req	A	3
1	4		Waste&emission	B	7
1	5		Social	B	7
1	6				
1	7				
1	8				
2	3	Supply Chain	Material req	A	2
2	4		Waste&emission	B	9
2	5		Social	B	6
2	6				
2	7				
2	8				
3	4	Material req	Waste&emission	B	8
3	5		Social	B	4
3	6				
3	7				
3	8				
4	5	Waste&emission	Social	A	2
4	6				
4	7				
4	8				

Figure C-1: Example assessment form, adapted from (Goepel, 2013).

D. Appendix D

Questionnaire for ship repair yard data collection is as follows:

Circular Economy Metrics for Ship Repair Yards

This study explores how circular economy metrics can be used in shipyards for repair operations in the shipbuilding sector. This study is part of doctoral research at the University of Strathclyde that focuses on applying circular economy principles in the maritime industry to extract more value from marine assets at the end of their life cycle.

Please answer all the questions. If you are unsure or do not know the answer to any question, please indicate so in your response. The information you provide will be used for research purposes and kept confidential. You do not need to provide any personal or identifying information.

Thank you for taking the time to participate in this study; your contribution is greatly appreciated.

Circular Economy Metrics for Ship Repair Yards

What is the circular economy?

The circular economy, a model focused on sustainable resource management and waste reduction, involves keeping materials in use for as long as possible. Unlike traditional economies, which often use make-use-dispose flows, the circular economy aims to keep materials in the loop as much as possible and as long as possible, so it seeks to extend the lifespan of resources and minimise waste.

6R Circular Economy Principles

The 6R principles of the circular economy outline strategies for different stages:

Reduce: Starting with product design, this aims to use resources and energy more efficiently. The 'Reduce' principle aims to minimise the amount of resources used in products and services to prevent waste before it occurs.

Redesign: This means designing products to last longer, be easier to maintain, and be recyclable. Choosing environmentally friendly and sustainable materials is crucial during this phase.

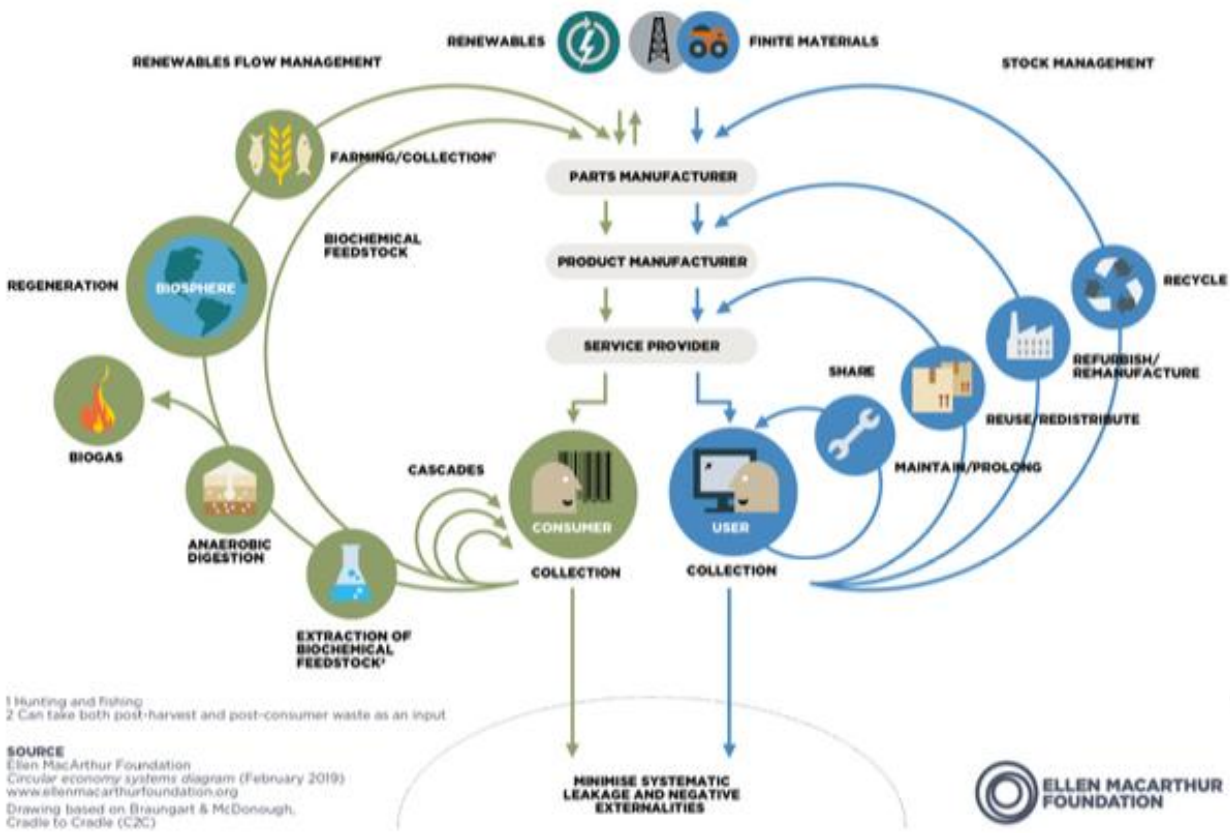
Reuse: This involves using products or components repeatedly without processing or remanufacturing. This is an effective way to reduce waste and can mean using products or materials for purposes other than their original intent.

Remanufacture: Remanufacturing involves restoring used products or their parts to like-new condition. This process often involves disassembly, cleaning, repairing, or replacing worn parts before reassembling them into fully functional products. Remanufacturing aims to efficiently extend the useful lifespan of products by refurbishing them to their original performance.

Recycle: It is the process of collecting and processing materials that would otherwise be discarded and turning them into new products. Recycling plays a crucial role in reducing waste.

Recover: Recovery in the circular economy refers to extracting valuable resources or energy from waste that cannot be reused, repaired, remanufactured, or recycled. This includes energy recovery from waste-to-energy processes and the extraction of materials from complex waste streams.

These principles form the foundation of the circular economy, emphasising the efficient use of resources and the reduction of waste.



Authors' Note

Before listing the metrics in the next section, we want to emphasise that consistency is critical in corporate performance tracking. This survey is focused on your organisation's 2023 results, which will form the basis for your circularity performance monitoring journey. The authors suggest that annual reporting and monitoring of circularity metrics will provide valuable insights into your organisation's progress towards sustainability goals. Consistently monitoring these metrics enables your organisation to pinpoint areas for enhancement and make informed decisions to improve its circular economy practices.

LEAD TIME

1. **RS-CM 1. Spare parts lead time for maintenance and repairs:** *

What is the ratio of the average lead time of remanufactured parts or components used in the ship repair process to the lead time of original brand-new parts and components in 2023?

This question relates to your overall operation in 2023, not specific to individual jobs or parts.

Note: Remanufactured parts and components refer to parts that are considered certified remanufactured or refurbished. This includes manufacturer-approved parts remanufactured by the OEM, such as reman fuel injectors, turbochargers, and purifiers, and excludes non-authorised industry-made replacement parts (such as will-fits).

____

[Response unit: %]

RRR content ratio

2. **RS-CM 2. Proportion of reused parts in repairs:** *

What is the ratio of reused (combined number of remanufactured and reused parts) in repairs to all parts used (combined number of new, remanufactured, and reused parts) in 2023?

This question relates to your general repair operation in 2023 but is not specific to individual jobs or parts.

Note: Remanufactured parts and components refer to parts that are considered certified remanufactured or refurbished. This includes OEM-remanufactured parts that have received manufacturer approval, such as reman fuel injectors, turbochargers, and purifiers, but excludes unapproved replacement parts made by the industry (such as will-fits).

Reuse parts, on the other hand, refer to parts that are dismantled during repair and reused after being repaired by the shipyard or its subcontractors or suppliers (e.g., polishing, honing, etc.).

____

[Response unit: %]

3. **RS-CM 3. Proportion of reused parts in maintenance:** *

What is the ratio of reused (combined number of remanufactured and reused parts) in maintenance operations to all parts used (combined number of new, remanufactured, and reused parts) in 2023?

This question relates to your general maintenance operation in 2023 but is not specific to individual jobs or parts. Maintenance operations include, but are not limited to, main and auxiliary engines, pumps, cranes, hydraulic equipment, etc.

Note: Remanufactured parts and components refer to parts that are considered certified remanufactured or refurbished. This includes OEM-remanufactured parts that have received manufacturer approval, such as reman fuel injectors, turbochargers, and purifiers, but excludes unapproved replacement parts made by the industry (such as will-fits).

Reuse parts, on the other hand, refer to parts that are dismantled during repair and reused after being repaired by the shipyard or its subcontractors or suppliers (e.g., polishing, honing, etc.).

____

[Response unit: %]

Reverse supply chain

This section focuses on parts removed from ships and returned to the original equipment manufacturer (OEM), an authorised dealer, or an independently certified remanufacturer for remanufacturing in 2023.

4. **RS-CM 4. Volume of returns:** *

For all repair and maintenance jobs in 2023, what is the ratio of core parts and components returned for remanufacturing to the total number of core parts and components removed to be replaced?

Note: The metric measures the percentage of core parts or components sent to the manufacturer (OEM) or a licensed third-party remanufacturer. This question pertains to your overall operation in 2023, not specific to individual jobs or parts.

____

[Response unit: %]

5. **RS-CM 5. Quality of returns:** *

Related to the previous question, the quality of the returned core parts in 2023 is questioned. What is the percentage of returned parts that are found suitable for remanufacturing?

Note: The metric measures the percentage of core parts or components sent to the manufacturer (OEM) or a licensed third-party remanufacturer of remanufacturable quality. This question pertains to your overall operation in 2023, not specific to individual jobs or parts.

____

[Response unit: %]

Financial impact

6. **RS-CM 6. Circular revenue generated:** *

This indicator focuses on the proportion of parts and component sales related to circular practices over total parts and component sales revenues in 2023. Based on your revenue from parts and equipment sales in 2023, what percentage is associated with circular products and circular economy practices (RRR— reuse, remanufacture, recycle)?

Note: This question pertains to your overall operation in 2023, not specific to individual jobs or parts.

____

[Response unit: %]

Customer involvement

7. **RS-CM 7. Ratio of customers who purchased circular parts and components:** * Please indicate what percentage of the customers you served in 2023 were supplied with remanufactured or reused parts.

For instance, if 90 out of 150 customers you served in the previous year received remanufactured and/or reused parts, you would divide 90 by 150.

____

[Response unit: %]

Waste and emissions

This section asks for information about the waste and emissions produced due to ship repair operations in 2023.

8. **RS-CM 8. The ratio of hazardous waste generated:** * Please indicate the ratio of hazardous waste produced to the total amount of waste produced as a result of all your repair and maintenance activities in 2023.

____

[Response unit: %]

Note: Since this is a negative factor and less hazardous waste is more circular, we will calculate the circularity score as: RS-CM 8_{score} = [1 – (Your Input)]

9. **RS-CM 9. GHG emission reduction due to circular options:** * Please indicate the percentage of GHG emissions that you mitigated as a result of using circular practices in 2023.

____

[Response unit: %]

Thank you!

Thank you for your participation! If you would like to hear about the research results and be updated, please leave your e-mail address below.

10. Your e-mail address (optional)

____

E. Appendix E

Maritime circularity metrics validation workshop participants are as follows:

Participant No	Maritime Industry Experience	Background	Current Stakeholder Group
1	16 years	Naval architect, senior design engineer. Experienced in cargo vessel design. Has worked at shipyards and ship design offices during their career.	Shipyard (new building)
2	9 years	Naval architect who has worked at shipyards as a structural engineer and quality assurance engineer.	Shipyard (new building and repair)
3	17 years	Senior mechanical engineer specialising in outfitting and production with intensive shipyard experience.	Shipyard (new building and repair)
4	15 years	Marine engineer by training with a master's degree in naval architecture, working as a project manager and engineering team leader. Experienced in repair, refit and retrofit operations.	Shipyard (repair)
5	13 years	Naval architect by training who has worked at different shipyards as an operations manager, currently serving as the general manager of the ship repair division at a private shipyard.	Shipyard (repair)
6	23 years	Captain by training currently working as a fleet manager for a ship owner/operator company, with the first 10 years of experience spent sailing onboard.	Ship Owner/Operator
7	32 years	Ship owner with a fleet of 7 vessels, including general cargo and dry bulk carriers.	Ship Owner/Operator
8	14 years	Marine operations manager, marine engineer by training, currently overseeing the day-to-day operations of a shipping company with 22 vessels.	Ship Owner/Operator
9	9 years	A mechanical engineer by training, has significant experience in two different maritime OEMs. First, the manufacturer of fluid separation and treatment products. Second, an engine manufacturer.	OEM
10	13 years	Naval architect by training, has worked for one of the biggest engine manufacturers in the industry. An expert on marine engines.	OEM
11	21 years	Naval architect by training, has worked at an OEM's engine manufacturing plant for years. Currently works as a product manager and is responsible for certain types of engines in the EAME region.	OEM
12	12 years	Mechanical engineering technician by training, currently works as a shipbreaking manager	Recycling Facility

13	7 years	Mechanical engineer by training. Has worked as a health and safety engineer in shipyards and ship recycling facilities.	Recycling Facility
14	13 years	Marine engineer by training. Has been working as a shipbreaking engineer for 8 years. Had sailed during the first five years of their career.	Recycling Facility
15	8 years	Naval architect by training. Specialised in ship performance, resistance, and powering. Works as a consultant at an IACS member classification society.	Classification Society
16	22 years	Naval architect by training. Has worked at several shipyards, and since 2008, they have worked at two IACS member classification societies. Currently works as a senior marine inspector and lead auditor.	Classification Society
17	17 years	Naval architect by training. Has worked at different levels of classification societies, from surveyor to branch manager. Currently founded their own company providing project management, certification, and consulting services in the maritime industry.	Classification Society
18	21 years	Naval architect by training with further MSc and PhD in naval architecture, experienced at multiple IACS member classification societies, and an expert on auditing, marine inspection, standards, and regulations.	Classification Society
19	10 years	Naval architect by training, has an MSc degree as well. Has been working as a senior design engineer, specifically focused on machinery and outfitting designs.	Ship Designer
20	27 years	Naval architect by training. Has worked in various roles as a surveyor and ship design expert. Currently works as a director of an international ship design and consultancy company.	Ship Designer
21	13 years	Naval architect by training, and has an MSc in engineering management. Works as a design engineer lead at a group of companies that have shipyards amongst their group as well.	Ship Designer
22	11 years	Industrial engineer by training. Currently works as planning and inventory control manager of an international company that imports and exports construction equipment and spare parts by sea, land, and air transport.	Cargo Owners
23	17 years	Has a business management degree and a master's in economics of international trade. Had worked as an international trade manager in various tech companies. Currently works as an export sales manager at a large steel mill group of companies with more than 12,000 employees.	Cargo Owners
24	14 years	Has a business management degree, and previous experience in customs operations. Currently working as a trade compliance and shipping manager at an international fast-moving consumer goods company.	Cargo Owners
25	18 years	Captain by training. Has an MSc in supply chain management, and a PhD in naval architecture. Previously worked at European national shipping authorities and currently works as an academic and an IMO delegate.	Local or International Authorities
26	8 years	Has an environmental engineering degree and an MSc in sustainability and environmental studies. Has worked at international and local authorities and is currently working	Local or International Authorities

		at a European national authority as a senior sustainability specialist.	
27	22 years	Has an engineering background with an MSc in environmental engineering and sustainability. Has worked as an environmental consultant, operations manager, and surveyor at various maritime companies, including coast guard and flag authorities. Currently working as a consultant at the department for maritime policies in the Ministry of Transport.	Local or International Authorities

F. Appendix F

Initial stakeholder engagement event questions in research Phase I are as follows:

i. In-person semi-structured interview (30/06/2022 in Tuzla, Istanbul):

Part I: General understanding and barriers

1. What challenges do you face in implementing circular economy principles within your organisation or projects?
2. How do current regulations and standards impact your ability to adopt CE practices?
3. In your opinion, what are the main barriers to achieving a closed-loop supply chain in the maritime sector?

Part II: Digital Infrastructure

4. Do you currently use any digital tools or platforms to track the lifecycle of marine components or vessels? If so, how effective are they?
5. How could a centralised digital platform benefit your operations in terms of material tracking, remanufacturing, or recycling?
6. What challenges do you foresee in adopting a digital infrastructure for enabling CE practices?

Part III: Remanufacturing and resource recovery

7. What is your experience with remanufacturing or repurposing marine components?
8. How do you perceive the feasibility of a remanufacturing hub in your region or industry?
9. How could collaboration between OEMs, shipyards, and engineering consultancies improve resource recovery and remanufacturing efforts?

Part IV: Collaboration and knowledge sharing

10. How open are you to collaborating with third-party stakeholders (e.g., shipyards, OEMs, consultancies) to improve circularity practices?
11. What role should industry-wide collaboration play in achieving CE in the maritime sector?
12. What specific knowledge gaps or training needs do you think stakeholders must address to make CE viable?

ii. Online workshop (12/12/2022)

1. How do you perceive the relationship between circularity and decarbonisation in the maritime industry? Are these concepts complementary, or do they present conflicting priorities in certain contexts?
2. What potential synergies exist between circular economy principles and decarbonisation efforts in the maritime sector?
3. How can digital tools, such as digital twins, IoT, or AI, bridge the gap between circularity and decarbonisation?
4. What metrics or indicators could effectively capture the mutual progress of circularity and decarbonisation in maritime operations?
5. What role can academia and consultancy firms play in fostering a better understanding of the interdependencies between circularity and decarbonisation?
6. What knowledge gaps need to be addressed to better integrate circularity and decarbonisation in the maritime industry?

iii. In-person Workshop 1 (23/01/2023 at Watermen's Hall, London):

1. Which stakeholder group has which roles in the circular economy transition?

    a. Current roles
    b. Future roles
2. How can we improve the reverse supply chain for end-of-life maritime assets?
3. Would take-back or servitisation strategies work in the maritime industry?
4. What are the circularity enablers at the onboard equipment level?
5. What are the circular economy enablers at the overall ship level?
6. Which key performance indicators are suitable to measure maritime stakeholders' circularity?
7. In your opinion, what are the critical needs of the maritime industry to successfully transition to a circular economy model?

iv. In-person workshop 2 (20/02/2023 at Cranfield University):

1. How do you perceive the relationship between circularity and decarbonisation in the maritime industry? Are these concepts complementary, or do they present conflicting priorities in certain contexts?
2. What potential synergies exist between circular economy principles and decarbonisation efforts in the maritime sector?
3. How can digital tools, such as digital twins, IoT, or AI, bridge the gap between circularity and decarbonisation?
4. What metrics or indicators could effectively capture the mutual progress of circularity and decarbonisation in maritime operations?
5. What role can academia, regulatory bodies, and consultancy firms play in fostering a better understanding of the interdependencies between circularity and decarbonisation?

6. What knowledge gaps need to be addressed to better integrate circularity and decarbonisation in the maritime industry?

v. Online Interview 1 (14-10/2023 with ship repair yards and recyclers):

Part I: Current practices and challenges

1. What are the main challenges you encounter in recycling or repairing maritime assets at their end-of-life?
2. How can current ship repair and recycling practices be improved to align with CE principles?
3. What specific barriers exist for you in recovering high-value materials or components for reuse?

Part II: Role of asset tracking in CE

4. How important is it to track marine components and materials throughout their lifecycle to enable circular practices such as remanufacturing, reuse, or recycling?
5. What types of data or systems would you find most helpful for improving material recovery in repair or recycling operations?
6. Do you currently use any tracking methods (manual or digital) to account for reusable or recyclable parts? If so, what are their limitations?

Part III: Integration of lifecycle thinking

7. How can lifecycle thinking be better integrated into your operations to support circularity?
8. Would you see value in incorporating tools that evaluate a component's circularity potential (e.g., identifying reusable or remanufacturable parts)?

Part IV: Certification and standards

9. How important is certification (by OEMs or classification societies) for remanufactured components in encouraging their use?
10. What challenges do you foresee in certifying remanufactured or recycled parts for maritime applications?
11. How could certification schemes be standardised to support circularity in ship repair and recycling?