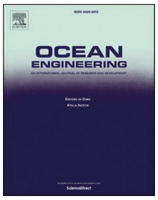
Ocean Engineering 312 (2024) 119158

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Research paper

Developing circularity metrics for the maritime industry: A stakeholder focused study

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ARTICLE INFO

Keywords:
Circular economy
Circularity metrics
Circularity indicators
Maritime industry
Sustainability
Maritime decarbonisation

ABSTRACT

Embracing circular practices is crucial for reducing the maritime industry's environmental impact. However, the industry lacks tailored circular economy metrics to effectively measure its circularity practices and performance. To address this gap, a comprehensive review was conducted, analysing over 400 circularity metrics used in various other industries. From this extensive review, these metrics were refined and adapted to develop 57 circularity metrics tailored to the maritime sector. These novel metrics aim to guide maritime stakeholders in assessing and improving their circularity performance. Their relevance was validated through stakeholder engagement and consultations, and practicality was demonstrated through a detailed case study in three private shipyards. This case study showcased the metrics' applicability and highlighted their potential benefits in real-world scenarios by providing suggestions for improving the circularity performance of the facilities. This study marks the first comprehensive maritime circularity assessment, providing a structured pathway for the future adoption and implementation of circularity principles within the maritime industry. By establishing these metrics, the study sets a foundational framework for stakeholders to enhance sustainability and promote circular economy practices in maritime operations. Quantifying circular economy performance will enable stakeholders to track progress, identify best practices, and drive transition.

1. Introduction

The circular economy (CE) is an economic model that aims to minimise waste, promote sustainability, and reduce the consumption of finite resources by keeping products and materials in use for as long as possible. The circularity concept is at the core of the CE and refers to the ability of products and materials to be part of a closed-loop system (Sassanelli et al., 2019) where they can be reused, repaired, refurbished, or recycled at the end of their service life (Blomsma and Tennant, 2020). These principles aim to extend the lifecycle of products and reduce the environmental impact of resource extraction and waste generation (Sassanelli et al., 2019). Furthermore, these principles emphasise the importance of designing products with longevity and sustainability, paving the way for a more resource-efficient and environmentally friendly economy. 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 and

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https://doi.org/10.1016/j.oceaneng.2024.119158
Received 15 March 2024; Received in revised form 30 August 2024; Accepted 1 September 2024

Granta Design, 2019). Fig. 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.

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 and 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. Furthermore, it should be noted that circularity does not necessarily equate to sustainability, and there are instances where CE policies might not lead to desired sustainable outcomes. While circular economy principles aim to reduce waste, optimise resource use, and extend product lifecycles, these measures alone do not automatically result in sustainability. The concept of rebound effects (Berkhout et al., 2000) and Jevon's paradox (Alcott, 2005) are critical in this context, as increased efficiency in resource use can lead to reduced costs, which might encourage higher consumption rates, thus counteracting the initial environmental benefits (Korhonen et al., 2018). Therefore, the transition to sustainability requires a holistic approach, considering direct and indirect circularity impacts.

The transition into CE is also essential for the maritime industry, as it is the most energy-efficient transport mode and the backbone of the global economy since it moves over 80% of world trade by volume, which is predicted to triple by 2050 (UNCTAD, 2022). On the other hand, the maritime industry still has a lot 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., 2023a). 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., 2023b). Moreover, considering the maritime industry's pledge to reduce its operational GHG emissions (Milios et al., 2019) – initially by 50% by 2050 (IMO, 2018), and then raising the bar to at least 70% in 2040 (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., 2023b).

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 efficiently classify these metrics. On the other hand, until now, there has been no way to track progress and ensure that maritime circularity transition is measured (Okumus et al., 2023a). Only ports have been addressed among all maritime stakeholders so far in terms of CE indicators (Faut et al., 2023). There is a clear gap within the

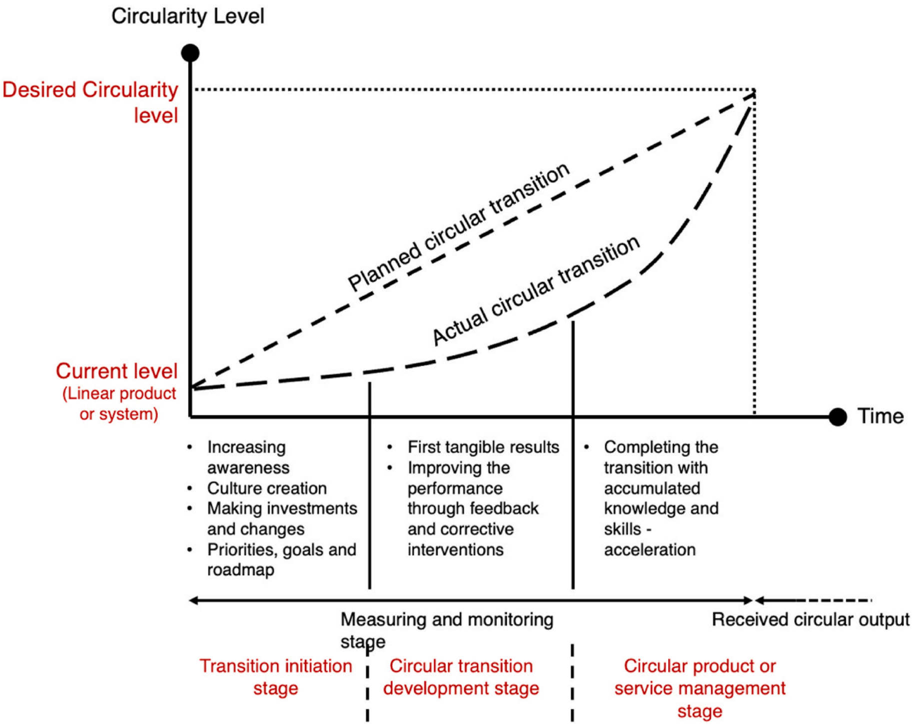


Fig. 1. Differences between the designed and actual circular economy transition, adapted from *(Ellen MacArthur Foundation and Granta Design, 2019)*.

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 which will enable 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. Currently, the maritime industry is approaching the CE concept with a main 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 research aims to explore and develop a set of circularity-specific 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, we conducted a stakeholder engagement activity to identify the current circularity practices, gaps and needs of the industry. This was followed by a thorough review of existing CE indicators as documented in the literature. Subsequently, the relevance of these indicators to the maritime industry was examined, conducting an initial filtering process to identify the most relevant ones. Building upon this, these indicators were consolidated and refined, shaping them into a set of metrics tailored specifically for the maritime sector, considering significant stakeholders and all life cycle stages. To ensure these metrics' practicality, effectiveness and validity, workshops and interviews with maritime stakeholders were organised. 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-specific indicators for the maritime industry and a novel contribution to the literature and knowledge. This research is the first time that indicators for CE were 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 were produced. This thorough approach ensures not only completeness to the set of metrics but also 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 paper is structured into six sections. Section 2 presents the literature review on CE metrics and indicators, Section 3 outlines the materials and methods used in this research. Section 4 presents circularity metrics developed for maritime stakeholders and associates the metrics with major industry aspects. Section 5 illustrates the case study, and Section 6 discusses findings and future perspectives.

2. Literature review on 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 a 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. The researchers demonstrated how to manage various end-of-life product (plastic waste) streams with different quality levels as a case study. 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. 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 stakeholders of maritime as well.

Ellen MacArthur Foundation and Granta Design (2015) 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 and Granta Design, 2019). On the other hand, the metrics introduced are high-level only and 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 approach of Di Maio et al. (2017) comprises monetary values of gross output, energy, material, and service costs to produce the output. 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 and demonstrated through gold minerals in mobile phones. Metrics considers when a resource 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 various countries. 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 covers 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, failing to address the unique nature (custom-made product and operational process) 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 original equipment manufacturers (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, including 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 3 R 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 levels of assessment.

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 along with the initial product lifespan, focusing on precious metals in mobile phone handsets. 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 available 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 more recent efforts is the ISO's 59,000 family of standards, which provides a structured framework for implementing CE principles; notably, 59,020 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, highlighting 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, our research will enable maritime organisations to accurately assess their circularity levels and identify areas for improvement. This will ultimately contribute to the overall sustainability and efficiency of the maritime industry, aligning it with the principles of a circular economy.

3. Materials and methods

This study was conducted in four main steps as shown in Fig. 2. Firstly, initial stakeholder engagement was undertaken in the form of 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 pertaining to 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?
- Which stakeholders can this indicator be applied to?
- 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, providing further validation of the metrics.

3.1. Initial stakeholder engagement

Three circular economy workshops were organised to understand the research need in maritime circularity (Okumus et al., 2023). Two workshops were carried out in person, and one was online, and all took place between December 2022 and February 2023 and attended by 71 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 for measuring and monitoring 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.

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 better understand CE performance?

To answer these questions, a systematic literature review was conducted. The research protocol was developed by defining the inclusion and exclusion criteria (Table 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 were gathered. This

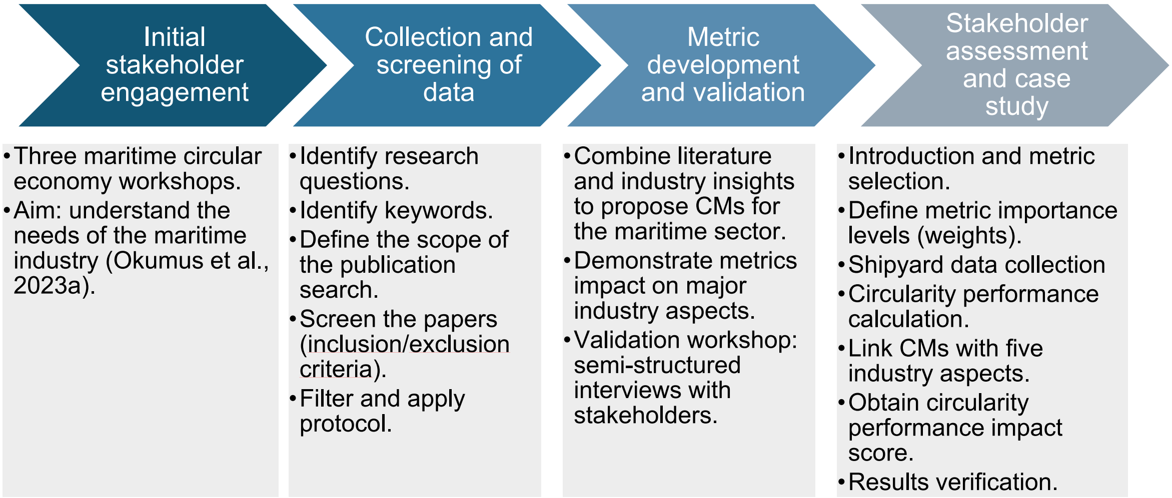


Fig. 2. Methodology.

Table 1
Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria		
	First filter	Second filter	Third filter
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).	Scan of abstract. Check that paper meets inclusion and exclusion criteria.	Read of full paper (57).

initial search provided ample papers for the purpose of this study, and it was deemed satisfactory to end the search at these databases.

The filtering process (Table 1) 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.

3.3. Metric development and validation

The indicators and metrics 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 metrics and indicators 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, the authors ran a final assessment of the indicators by asking the following questions.

- Does this indicator show circularity performance for maritime?
- Which maritime stakeholders can this indicator be applied to?
- 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 by authors by adapting 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. 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.

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 B 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 5: Case Study for Repair Yards.

4. Results and analysis

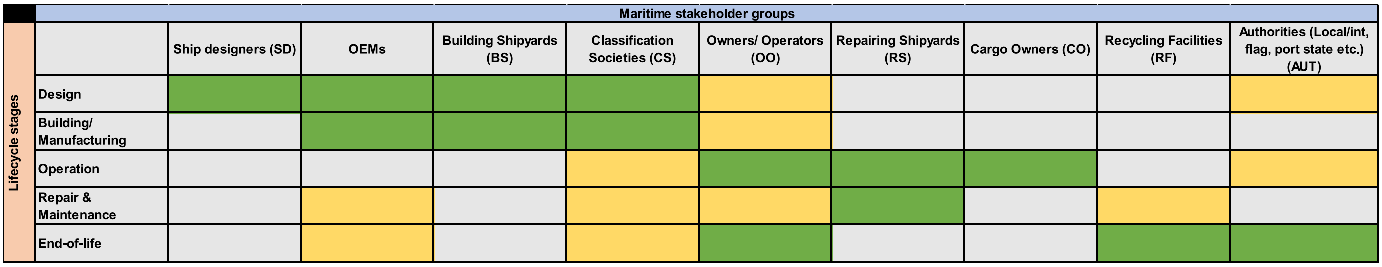
4.1. Stakeholder focused circularity assessment

In this section, the authors propose 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. At this point, Fig. 3 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).

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 circular economy initiatives by providing stakeholders with the freedom 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 authors have 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., 2023). 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. 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. Fig. 4 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 A-7 in Appendix A gives a brief list of the metric definitions.

Moreover, depending on the availability of the participants, smaller



Lifecycle stages	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)
Design	🟩	🟩	🟩	🟩	🟨				🟨
Building/ Manufacturing		🟩	🟩	🟩	🟨				
Operation				🟨	🟩	🟩	🟩		🟨
Repair & Maintenance		🟨		🟨	🟨	🟩		🟨	
End-of-life		🟨		🟨	🟩			🟩	🟩

Fig. 3. Connection between vessel lifecycle stages and maritime stakeholder groups.

workshops or semi-structured stakeholder interviews have been carried out for each stakeholder group to validate, 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, 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 4.2.

4.1.1. 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 (1).

$$[SD - CM\ 1] = \frac{Average\ design\ life\ of\ ships\ designed_{annual}}{Average\ lifespan\ of\ same\ class\ vessels_{\ annual}} \qquad \text{(Equation 1)}$$

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 A-1 in Appendix A.

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 (2).

$$[SD - CM\ 3] = \frac{W_{recycled\ or\ reused\ materials}}{W_{\ total\ materials}} \qquad \text{(Equation 2)}$$

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 (3).

$$[SD - CM\ 4] = \frac{C_{remanufactured,refurbished\ or\ reused\ components}}{C_{new,remanufactured,refurbished\ or\ reused\ components}} \qquad \text{(Equation 3)}$$

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 (4), where *N* stand for the number of customers.

$$[SD - CM\ 5] = \frac{N_{customers\ provided\ circular\ designs}}{N_{total\ customers\ served}} \qquad \text{(Equation 4)}$$

4.1.2. 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 A-2 in Appendix A presents a predefined three-level scale, for example, the onboard marine engine modularity score.

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

	Maritime stakeholder groups										
Circularity Metric Themes		Related References	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	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	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			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

Fig. 4. An overview of developed CMs within this study.

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.

$$[OEM - CM\ 4] = \frac{t_{new}}{t_{reman}} \qquad \text{(Equation 5)}$$

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 A-3 in Appendix A 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 A-4 in **Appendix A**.

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.

4.1.3. 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 A-1 in Appendix A 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 (6). The durability indicator is recommended to be measured annually.

$$[BS - CM\ 4] = \frac{VLS_{built}}{VLS_{world\ average}} \qquad \text{(Equation 6)}$$

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.

4.1.4. 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.

4.1.5. *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 A-5 in Appendix A.

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 A-5 in Appendix A 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 A-6 in Appendix A.

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., 2024) 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 A-5 in Appendix A) can be adapted to measure the CS-CM 5 score.

4.1.6. *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 recycled 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).

$$[OO - CM\,6] = \frac{W_{total}}{LDT_{vessel}} \qquad \text{(Equation 7)}$$

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.

4.1.7. 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., 2023a). 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.

4.1.8. 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 (8).

$$[CO - CM\,1] = \frac{\left(W_{cargo} * \ distance\right)_{circular}}{\left(W_{cargo} * \ distance\right)_{total}} \qquad \text{(Equation 8)}$$

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.

4.1.9. 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 authors have 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.

4.2. Major industry aspects and impact

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 De Pascale et al. (2021)'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 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 and 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. (2023b). 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.

5. Case study for ship repair yards

5.1. 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 2 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 improved resource efficiency and waste reduction.

Considering material circulation from repair and maintenance activities, the authors 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.

Table 2
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
Shipyard C	Marmara Region, Turkey	60,000 m2	1 graving dock up to Panamax size	1,000,000 DWT per annum

5.2. Case study steps and findings

An eight-step application plan has been devised for the case study, as depicted in Fig. 5. The plan includes introducing the circularity concept, carrying out baseline assessments, setting specific circularity targets, enabling CE performance calculation, and monitoring progress to improve repair shipyard operations continuously. By following these steps, the shipyards can identify areas for improvement and gradually increase their circularity performance. By doing so, they can contribute

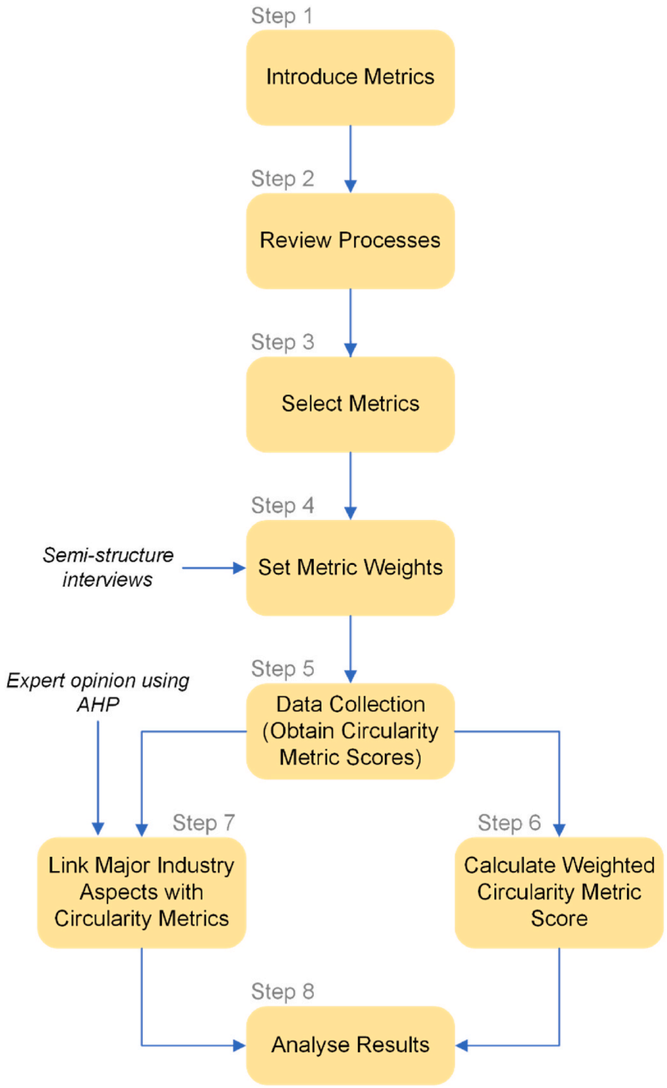


Fig. 5. Case study steps.

to a more sustainable maritime industry.

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.
2. The research team has examined general ship repair process flows of each shipyard and discussed them with their engineering staff to capture their internal processes and ensure the same scope is set for each facility.
3. Metric selection: In this step, considering data availability or other factors preventing transparent information sharing, some of the metrics can be excluded before proceeding to assign their 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.
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 authors 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 3 Before proceeding, the research team presented the final weights to Shipyards A, B, and C, who approved and agreed upon the final table.
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 authors prepared an online questionnaire (disclosed in Appendix B), and considering their 2023 business results, three shipyards provided their circularity scores using the metric definitions in Section 3.1.4. When needed, the authors supported the shipyard professionals who had to dive into their organisations' operational and financial year-end figures to calculate the requested metrics.
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 4 and Fig. 6. 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.

Table 3
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%

Shipyards B, A, and C have total circularity scores of 54.88, 43.00, and 37.00. Comparing their CM scores at individual levels reveals that no single shipyard dominates, with Shipyard A or Shipyard C excelling in various metrics.

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 circular spare parts availability 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 behind 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).

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 in the conclusion and discussion sections.

7. Considering the five dimensions explained in Section 4.2 (financial, supply chain, material requirements, 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 5 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 A-1* in Appendix A presents an example assessment form used in this stage. The final results of this process are provided in Table 6.Based

Table 4
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		

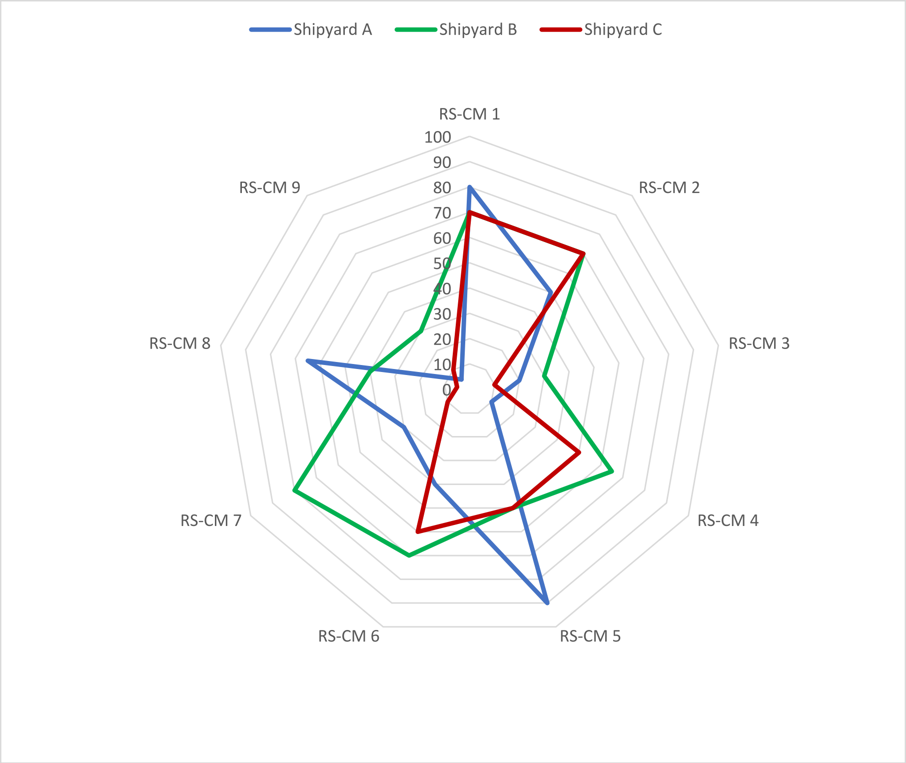


Fig. 6. Shipyards' performance on each circularity metrics.

Table 5
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

on the AHP results, the nine circularity metrics in this case study demonstrate a relatively even representation across the five aspects. 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 6 provide detailed information about the association of metrics with each aspect and the degree of association.

Table 6
Major industry aspects and circularity metrics connection levels.

Circularity Metrics	**Major Industry Aspect Connection Levels (ACL)**				
	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%
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%
ΣAspect Weights	195.6%	153.9%	220.0%	180.0%	150.6%
Normalised Weights	**21.7%**	**17.1%**	**24.4%**	**20.0%**	**16.7%**

8. Combining the outcomes of Step 7 and Step 5, the participant organisations' performance levels on the five aspects have been obtained using Equation (9) below. The results, depicting the performance of each shipyard based on the developed circularity metrics, are illustrated in Fig. 7.

$$PS_{i,j} = \frac{\sum_k (ACL_i * CMS_j)}{\sum_i ACL_i} \ \forall i, j, k \qquad \text{(Equation 9)}$$

where PS, ACL and CMS correspond to Performance Score, Aspect Connection Level from Table 6, and Circularity Metric Scores from Table 4, 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).

The performance chart for the shipyards, presented in Fig. 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 6, 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

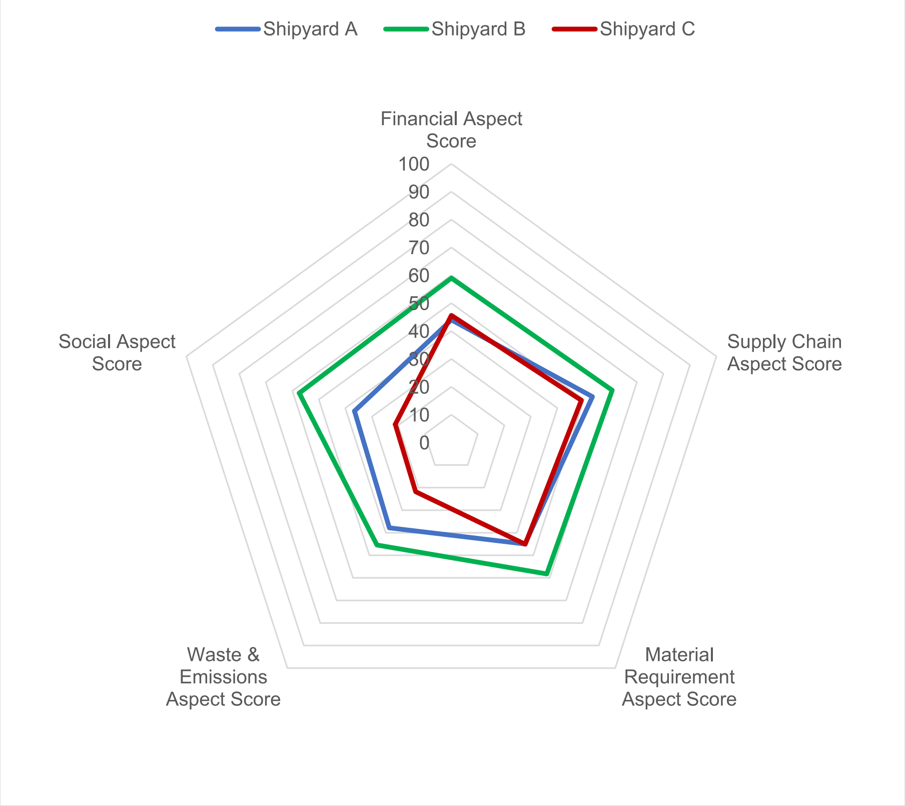


Fig. 7. The performance of the shipyards according to major industry aspects.

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 6, 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 similar to each other in three out of five aspects: financial, supply chain, and material requirement. There are certain circularity metrics in which Shipyard A performed even better than Shipyard B. These results indicate that all shipyards can benefit from benchmarking and best practice sharing strategies to improve their sustainability performance in key areas, and 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 keep monitoring their circularity levels regularly. In fact, the authors strongly advise annual assessments. In this way, the stakeholders could 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.

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.

6. Discussion and future perspectives

The maritime industry faces a sustainability challenge, and CE can play a crucial role in addressing this challenge. Indeed, to successfully implement CE and unlock all its benefits, circularity metrics specific to maritime stakeholders are required. These metrics can be game-changing for the maritime industry's CE transition journey. The indicators of the CE measure the extent to which a system or process is circular, i.e., minimising waste and maximising resource efficiency and value creation. Consequently, tailor-made metrics can help maritime stakeholders assess their current situation, identify their strengths and weaknesses, set their goals and targets, monitor their progress and results, and communicate and report their achievements and challenges. In other words, circularity metrics can also help maritime stakeholders to compare and benchmark themselves with other stakeholders and to collaborate and coordinate with other stakeholders to achieve circularity goals and outcomes.

Furthermore, successfully implementing CE practices within the maritime industry requires stakeholders' active participation and commitment. Understanding each stakeholder group's unique needs and contributions is vital for developing effective indicators or metrics to measure circularity. Additionally, fostering a culture of transparency and knowledge sharing among stakeholders can facilitate the identification of best practices and the development of innovative solutions for a more sustainable maritime industry.

Moreover, another critical point in measuring the circularity of a system or industry is connecting circularity metrics with major industry aspects that are most affected by circularity efforts, such as finances, supply chain, resource consumption, waste generation, and social impact. By integrating these metrics into structured frameworks and standards, stakeholders can track progress towards circularity goals more effectively and drive meaningful change within the maritime sector. This study successfully developed such a needed structured framework in the results section and further demonstrated how it can be implemented with a practical case study. However, it's crucial to note that the development of innovative metrics, especially those like OEM-CM 6 or RF-CM 3 (GHG emission reduction related indicators), often precedes 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 presents an opportunity for future research to build on this foundation, emphasising the importance of data-driven approaches to validate and refine these metrics further.

Despite the challenges, such as lack of alignment, transparency, data availability, and infrastructure, the maritime industry has started to move forward in its circularity transition. It is evident that awareness amongst the stakeholders seems to have been increasing (Okumus et al., 2023a), and there is a growing recognition of the importance of sustainable practices in the industry. While the industry lags behind other transportation industries, the authors believe that with maritime specific tools and approaches, the sector can start building up some momentum.

Looking ahead, this study provides valuable insight into the potential for circularity within the maritime industry and demonstrates through a case study. 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. Ultimately, this study sets the foundation for a more sustainable maritime industry, promoting the shift towards circularity and supporting the industry's endeavours to meet global sustainability targets.

Finally, maritime circularity metrics can form a basis 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. Furthermore, to ensure that CE practices are implemented in the maritime industry and contribute positively to sustainability, it is crucial to implement complementary policies from regulatory bodies such as IMO. These policies could include setting limits on resource use, implementing environmental taxes on resource use, and promoting product-as-a-service models that decouple consumption from resource use. Furthermore, educating designers, engineers, naval architects, shipowners, etc., for maritime about sustainable consumption and encouraging behavioural changes are required to reduce the demand-side pressures. Future research should focus on developing comprehensive frameworks that integrate CE practices with broader sustainability goals, ensuring that the environmental benefits are not only achieved but sustained over the long term. The maritime industry can work towards a more sustainable future by collaborating with all stakeholders and implementing standardised circularity metrics. Rewarding circular practices can help drive positive change and encourage widespread adoption of environmentally friendly initiatives within the industry.

7. Conclusion

The maritime industry needs CE metrics to progress towards circularity. This transition would benefit the environment for a resource-intensive industry through initiatives such as remanufacturing components, ensuring durability and longevity, and increasing material efficiencies.

This study conducted a systematic literature review and analysed over 400 CE indicators. The initial review found that no other CE indicators were being reviewed, designed, or utilised specifically for measuring circularity performance in the sector. As a result, this innovative study sought to investigate and establish particular circularity indicators for maritime stakeholders, including ship owners, shipyards, OEMs, recycling facilities, and others. The study identified, filtered and refined CE metrics to suit the unique requirements of the maritime sector. Stakeholders from the maritime industry were consulted to ensure that the indicators devised were fit for use and applicable.

Moreover, this study conducted a representative case study for repair shipyards to demonstrate how the metrics can be applied in practice. Three private shipyards participated in a case study to verify the effectiveness of the circularity metrics. The case study results have helped shipyards develop a plan to address their circularity issues. The case study also demonstrated the potential benefits of adopting circular practices. Additionally, the study underscores the importance of collaboration and knowledge exchange among stakeholders in the maritime industry to drive significant change and improve the industry's CE performance.

One of the limitations of this study is the number of facilities included in the case study section. Further investigations can be done supported with data to further improve the metrics. Moreover, due to data availability, the authors only presented the case study on ship repair yards. Future research can expand on this by examining other stakeholder groups, such as shipowners or operator companies and ship recycling facilities, to gain a more comprehensive understanding of the industry's progress towards sustainability. Moreover, stakeholders from other parts of the globe can be included (e.g. newbuilding yards from China, South Korea and EU) to set a benchmark for the industry globally. On the other hand, these case studies requires a collaborative effort due to the challenges of the industry such as lack of transparency, lack of standardisation of ships, lack of a database for such information and the lack of knowledge of practitioners on "what data to collect" to pursue CE and sustainability.

Likewise, future studies can focus on developing innovative technologies and business models that promote circular economy practices in the maritime industry. Additionally, exploring the initial investment required to enhance the circularity performance of an organisation and showcasing long-term cost savings through circular practices to mitigate financial concerns can be a substantial future study.

The circularity metrics are key for improvement in assessing CE practices accurately. Implementing these indicators could lead to a quicker and more efficient transition to circularity in the sector and allow for more sustainable and efficient operations within the industry. By addressing this gap in measurement and evaluation, stakeholders can better track their progress towards circularity goals and make informed decisions to improve sustainability. The results of this study can be instrumental in shaping future policy development and industry initiatives aimed at achieving a more sustainable maritime sector.

These metrics will also provide the opportunity to quantify circular economy practices in the maritime industry. For instance, metrics can be developed to measure the percentage of materials reused or recycled from vessels, the amount of waste diverted from landfills, and the lifespan extension of materials through 6 R. Furthermore, metrics can benchmark and compare the performance of different stakeholders such as owners, shipyards, recycling facilities, or even regions or countries. This can help identify best practices and areas for improvement and drive innovation and efficiency through best practice exchange. Moreover, metrics can support monitoring the environmental impacts such as emissions, energy, and resource efficiency of maritime assets, taking the entire life cycle into account. This can provide valuable insights into the industry's transition towards more sustainable and environmentally friendly practices. Furthermore, these metrics will enhance transparency and accountability in the industry by offering clear and measurable sustainability performance indicators to stakeholders, including regulators, investors, and the public. Moreover, leveraging metrics to understand circular economy principles can aid in identifying economic opportunities and potential cost savings through 6 R. These principles also promote improved resource management and the creation of new markets for 6 R or equipment, resulting in job creation in the remanufacturing, refitting, and recycling sectors.

Although the metric development and initial case study offered valuable insights for the maritime industry by demonstrating the metrics' suitability, further testing in different stakeholder environments is necessary to verify them and provide additional guidance and a circularity roadmap for the maritime industry (e.g., shipbuilding yards, ship recycling facilities, OEMs). Further case studies covering other stakeholders combined with a data collection campaign are necessary to demonstrate the complete set of metrics. Another improvement for this study can be the enhancement of the weightings applied in the analysis. This study only demonstrated the overall framework and the approach to apply these metrics. Moreover, researchers could explore other multi-criteria decision-making methods to further enhance the sensitivity of the results. Once the metrics are tested, a tool and database for circular economy performance can be developed to set benchmarks across the stakeholders in the industry. This approach will promote transparency and facilitate the exchange of best practices among stakeholders within and across the industry. The accumulated data on CE metrics can inform the development of policies and regulations that promote sustainable practices in CE. Governments and organisations can use this data to set targets, establish incentives, and drive the industry towards a more circular and sustainable future.

This study helped to close the current gap in circularity measurements for maritime stakeholders, resulting in a more comprehensive and holistic approach to sustainable practices in the sector. Finally, establishing these indicators contributed to a greater understanding of CE principles throughout the marine sector. It provided significant information for policymakers, corporations, and researchers seeking to promote circular practices in maritime operations. The findings of this study can serve as a valuable tool for guiding future policy development and industry initiatives aimed at achieving a more sustainable maritime sector.

CRediT authorship contribution statement

D. Okumus: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **E. Andrews:** Writing – review & editing, Investigation, Conceptualization. **S.A. Gunbeyaz:** Writing – review & editing, Visualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oceaneng.2024.119158.

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