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Towards a circular maritime industry: Identifying strategy and technology solutions

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ABSTRACT

Shipping is considered one of the most energy-efficient modes, considering the amount of cargo that can be carried. On the other hand, the circular economy approach is not well-established in the maritime industry, which currently lags behind different transport modes. The maritime industry needs scientific support to "close the loop", minimise waste and increase the revenue stream. Therefore, this study aims to address a critical gap in the maritime industry by first showing the understanding of the stakeholders and identifying suitable strategy and technology solutions that can fit the characteristics of the maritime industry. Moreover, the potential benefits of these solutions have been demonstrated through high-speed marine engine remanufacturing. A cost-benefit analysis has shown that remanufactured engine acquisition cost is nearly half of the cost of a new engine with similar operating performance and operating cost. This study is a novel contribution to maritime industry stakeholders to demonstrate the advantages of circular end-of-life applications.

1. Introduction

The circular economy (CE) is a crucial concept with substantial gains (Grafström and Aasma, 2021) and essential for overcoming future resource scarcity and the environmental damage the current linear economy approach is causing (Mitchell and James, 2015; Preston, 2012; MacArthur, 2013). The circular economy concept emerged as a response to the linear economy (Pearce and Turner, 1990), which is wasteful and dangerous to the environment (Michelini et al., 2017). Although the concept of 6R (redesign, reduce, reuse, recycle, remanufacture, repair) has become more prevalent in other industries, including the automotive and aeronautical transport modes, shipping presents a mixed overview (Gunbeyaz, 2019; McKenna et al., 2012).

The share of the maritime industry in total world trade is massive, given that around 90% of the goods are carried by marine vessels globally (Stopford, 2009). The size of the merchant fleet -thus the majority of maritime assets-is directly correlated with world trade volume. Therefore, it has particular importance in all transportation industries. About 85,000 ships sail globally, with more than 50% over 15 years old (Jansson, 2016). Although the maritime industry stands in such a remarkable position, it has severe gaps toward the circular economy – in terms of awareness and infrastructure.

The term circular economy is not well understood in the maritime industry, and the sector automatically focuses on the recycling stage when the circular economy is mentioned. The recycling of ships is widespread in the maritime industry (Fariya et al., 2019; Gunbeyaz et al., 2020). On the other hand, the practices in the ship recycling yards prevent the full utilisation of the industry's potential. Moreover, recycling is the lowest hierarchy of end-of-life (EoL) in a circular economy (MacArthur, 2013; Gilbert et al., 2017). It causes a reduction in quality while decreasing the useable life cycles (Wahab et al., 2018). Therefore, this study aimed to implement circular economy principles in the maritime industry by identifying the end-of-life scenarios for selected high-value items and investigating technology solutions to manage asset tracking for naval assets. Through this novel circular economy investigation of the maritime industry, the project addressed a critical understanding gap within the industry.

This study addresses a significant gap in the literature, considering the maritime industry lags behind the other transport modes. This is the first study in the maritime literature working on the identified strategy, technology and software solutions. It combines this with a case study to demonstrate the benefit of remanufacturing an engine for a ferry. The authors believe this study will guide the maritime industry to transform through circularity in the future, which is a must for the industry's sustainability.

On the other hand, in the maritime industry, the CE concept is not

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well-known by all stakeholders. Apart from OEMs, stakeholders tend to limit the CE with recycling scrap materials – mainly steel. Therefore, high-value components on board, such as diesel engines, are mostly underutilised compared to their reuse and remanufacturing potential (Okumus et al., 2022b).

Many well-known engine OEMs in the marine industry are concerned with circular economy subtopics, especially after-sales services. This research has investigated the circular options provided by renowned marine engine manufacturers, such as Wärtsila, Caterpillar, Volvo Penta, MTU and Cummins. Other OEMs in the sector, which the authors did not have the opportunity to examine within this study, might also carry out similar applications. According to the findings, all marine engine OEMs offer remanufacturing options up to a certain level. Some of them have founded worldwide *remanufacturing centres/facilities.* Also, there are some take-back strategies being carried out.

Some manufacturers tend to build strong OEM-dealer networks and capabilities to provide rebuilding and remanufacturing services across the globe. Some dealers invest heavily to reach the required capacity and capability for the circular economy principles. At the end of the day, engine remanufacturing operations naturally depend on customers' circular economy awareness level. Therefore, a strong OEM-dealer-customer collaboration is essential to increase the industry's awareness level and build mutual trust, which paves the way for higher adoption rates.

OEM-dealer-customer collaboration starts with the OEM-dealer part of the relationship. Manufacturer and dealer alignment on corporate branding strategies forms a basis for ensuring a strong relationship. In the literature, several researchers regarded an OEM as a channel manager who sets the tone for the channel and is accountable for generating dealer value (Anisimova and Mavondo, 2014). A manufacturer generates an incentive to retain the connection with dealers and accomplish strategic results by making key investments in the relationship. The success of a manufacturer-dealer relationship depends on several factors, including the manufacturer's reputation for fairness, marketing assistance, staff training, problem-solving competence and response, and timely support (Wu et al., 2004; Anisimova and Mavondo, 2014).

Regarding the dealer-customer side of the relationship, solutions and value-adding applications that benefit customers are essential to form and sustain a strong connection. Industrial brand management is defined by corporate-level branding, product-level innovation, and an emphasis on building more personal ties between buyers and sellers via customer satisfaction and commitment (Mudambi, 2002; Anisimova and Mavondo, 2014). This philosophy should be taken into account to assess OEM-dealer-customer relationships. The relationship between a dealer and customers can be improved by aftersales customer support approaches such as being a solution provider rather than a vendor, offering condition monitoring services, and developing tailor-made solutions (e.g. servitisation) for specific customer needs. Increasing the frequency of customer interaction, enhancing the information flow amongst the organisations, and creating fair and transparent communication are some of the key points.

Apart from OEMs and official dealers, there are 3rd party remanufacturers that provide component repair or rebuild solutions directly to ship owners. They are also crucial for the industry as they help diversify existing solutions in the market. Third-party service providers usually focus on repairing existing components on vessels since they generally aim to avoid certification processes. Nonetheless, their efforts contribute to extending the remaining useful time of onboard components.

Section 2 introduces materials and methods used in this research, while Section 3 summarises the technology and strategy solutions for CE applications in the maritime industry. Following that, Section 4 demonstrates the case study, and then Section 5 discusses findings and future perspectives for the maritime industry.

2. Material and methods

This study includes the steps shown in Fig. 1 to achieve the overall goal. First, a maritime circularity-focused questionnaire was designed and carried out in parallel with this study to discover the circular economy perception of the maritime industry stakeholders and reveal the maritime Original Equipment Manufacturers' (OEMs) capability and willingness toward circular economy principles (Okumus et al., 2022b). This comprehensive questionnaire included the shipowner/operator companies, building and repair shipyards, professionals, OEMs, ship recyclers, classification societies, and local or international authorities by reaching out to 83 participants in total The experts were contacted through the existing network by emails, social media and calls to the companies. The questionnaire has 33 questions in total, and it is tailored according to participants' backgrounds to discover the perspectives of different stakeholders. Each stakeholder group encounters different questions, and the quantity of questions also depends on their answers as it is structured with follow-up questions to elaborate on the participants' viewpoint and check for any conflict. For instance, while an OEM participant would encounter (re)manufacturing capability-focused questions, a shipowner is questioned about their perception of remanufactured components. If shipowners state that they do not prefer remanufactured products, this triggers two follow-up questions aiming to identify the main reasons for that viewpoint and trying to capture what would change their minds in favour of reman equipment. In this way, out of 83 responses, 21 were eliminated due to inconsistency or incomplete answers. While this paper does not cover the entire survey, it includes some key questions and responses.

Following the survey results, high-value and high-potential components on ships are identified. Marine engines are selected as a focus of the case study. Therefore, the study presents an engine rebuilding case study, starting with an investigation of how engine remanufacturing is carried out within the industry and following the procedure. Finally, a cost/benefit analysis is conducted for the remanufacturing operation.

3. Strategy and technology solutions for successful implementation of CE in the maritime

Strategy and technology solutions need to be investigated to achieve a circular maritime industry. Although many studies in the literature include case studies in various industries, none explicitly focus on the maritime industry. Therefore, this section examines the current remanufacturing and asset tracking applications in different sectors, which are also considered applicable to the maritime industry.

3.1. Strategic solutions

3.1.1. Closed loop supply chains (CLSC) and recovery hubs

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

CLSCs for remanufacturing have several more complicated characteristics than forward supply chains. First, the input of the remanufacturing process, which are the used product returns, is uncertain in means of quality, quantity and arrival time. Moreover, the elements of the core return side of the chain may differ from the forward distribution network. Secondly, due to the nature of the concept, returned products of different conditions will need other remanufacturing processes, resulting in extra time, cost, and capacity usage (Souza, 2014). A percentage of the returned products may be unsuitable for remanufacturing, so they will require recycling separately. Some everyday activities associated with product recovery in the reverse chain are used product

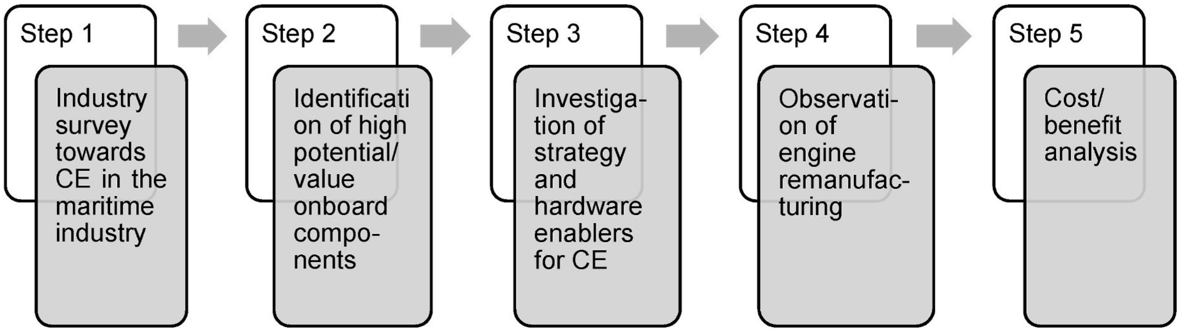

Fig. 1. Adopted research methods.

acquisition, reverse logistics, used product checks (testing and grading), remanufacturing and remarketing (Guide and Van Wassenhove, 2002). To establish reuse-remanufacture-repurpose principles in the maritime industry, maritime OEMs should especially consider used product acquisition and logistic aspects, from ship recycling yards to remanufacturing centres.

That brings us to the next point: product recovery hubs. Despite conventional forward supply chains, where facility location models provide the optimal configuration for the chain – such as the optimum number, location, and size of warehouses that minimise distribution and fixed costs; in CLSC, the firm also needs to locate consolidation centres/hubs for returns and recovery facilities for remanufacturing, recycling, or scrap disposal. Ideally, consolidation centres/hubs round-up returns from numerous sources, test them and route them to recovery facilities (Souza, 2013). This can be challenging for the maritime industry as stakeholder groups are distributed to different parts of the globe. While Asian shipyards dominate the new build market, the ship recycling stage is dominated by countries, namely Bangladesh, India, China, Pakistan and Turkey.

3.1.2. Seeding

Remanufacturing operations require a certain level of core parts inventory for a healthy start of reman production. At that point, seeding strategies might help the OEMs by accelerating the core part collection phase. Seeding is selling a certain number of new components or parts as remanufactured products to collect used parts to reach the targeted level of core inventory to initiate remanufacturing operations. The quantity of released new products is called the seed stock (Akçali and Morse, 2004). A higher volume of seeding stock implies that recovering more core components via a reverse supply chain will be possible throughout the planning horizon. Therefore, remanufacturing OEMs will be able to acquire the needed number of cores for efficient remanufacturing operation sooner (Abbey et al., 2018).

Many durable goods industries - such as automotive, power generation and heavy equipment – implement seeding since the lack of cores disrupts their remanufacturing operations. In fact, Abbey et al. (2018) stated that managers from companies like Caterpillar, Cummins and Delco Remy consider the seeding strategy as a valuable tool for reaching economies of scale earlier for both manufacturing and remanufacturing operations. According to Abbey et al.'s research in the diesel engine industry, it is discovered that seeding has the potential to increase total profit from remanufacturing up to 40% in the best scenario and around 23% on average. Thus, even if seeded units are sold at a loss, seeding can substantially increase the company's overall profits by making remanufacturing operations available earlier (Abbey et al., 2018).

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

3.1.3. Take back strategies: trade-in and leasing

Guide and Van Wassenhove's study in 2001 was one of the pioneers who introduced the idea of product acquisition management, where an OEM can control the timing, quantity, and quality of product returns through appropriate economic incentives to increase the profitability of recovery activities (Souza, 2013; Guide and Van Wassenhove, 2001). Today, trade-in policies offer customers some trade-in value (a discount or credit) for their used products during a sale, whether a new or remanufactured product. That way, while customers put their old equipment to good use, the OEMs trigger their reverse supply chain first-hand.

Trade-in applications are becoming increasingly popular, so they are about to become the standard, especially in saturated and high technology involving industries (Tozanli et al., 2020b). Considering the world merchant fleet's average growth rates, which are 3.3% in DWT and 1.8% in the number of ships (over 1000 GT) from 2016 to 2021 (Infomaritime Eu, 2021), one might conclude that it is saturated. Many global OEMs in the maritime industry are aware of trade-in policies, and there are good examples, such as Cummins, which executes trade-in strategies successfully. After purchasing a Cummins product, customers receive a discount if they return their old components or parts. The returned cores are shipped from dealers to Cummins' used product depot, and when they arrive, customers are given credit for returning the core components (Souza, 2013). Cummins is not alone in that regard. Other OEMs, such as Caterpillar, Volvo Penta and so on, also execute similar strategies. Apart from that, there are different approaches for determining optimum trade-in discount rates; some calculate the trade-in value proportional to the used product's age, while others offer a standard tariff. In general, Souza (2013) points out that remanufactured engines and engine parts are sold at around a 35% discount compared to new alternatives.

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

Apart from trade-in and leasing strategies, OEMs can also influence the used value of a product in the second-hand market by charging a mandatory relicensing fee for products remanufactured by third-party companies (Oraiopoulos et al., 2012). This means that relicensing costs can effectively control the volume of both third-party and OEM remanufacturing operations. Relicensing fee is essential, especially when third-party remanufactured options challenge new and OEM remanufactured products. On top of that, even if it is remanufactured by a third-party remanufacturer (3 PR), the remanufactured product's quality is still dependent on the quality of the original new product by OEMs.

3.1.4. Product service solutions (PSS)

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

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

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

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

3.2. Software technology solutions

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

3.2.1. Industry 4.0 (I4.0)

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

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

As mentioned in previous sections of this study, maintaining control over the time, quality and number of cores returned is one of the most significant issues that remanufacturers encounter. At this point, the smart services concept is associated with technological solutions that enable advanced and disruptive product-service systems. As mentioned in the strategic solutions section, the PSS strategy can be significantly supported by technological advancements within the I4.0 umbrella. In an advanced PSS business model, which offers a pay-per-performance concept, OEMs or dealers/retailers maintain ownership of the product and only provide the service or use to consumers (e.g., selling "engine flying hours" rather than "engines"). As a result, the system requires proper product monitoring features throughout the operation and anticipation for remanufacturing processes on returned cores based on the product's estimated remaining life.

On the other hand, since buyers pay for the service rather than the product, market acceptability for remanufactured items will improve, resulting in a successful remanufacturing model. Predictive maintenance might be made possible by the early identification of faults by real-time monitoring of products in use and data analysis using embedded sensor networks and cloud computing. As a result of I4.0, the increased connection between products, consumers, and producers creates enormous potential for enhancing the product service model (Yang et al., 2018).

There are good examples from power generation industries—for instance, some OEMs lease well-equipped engines to power plants, where the utmost equipment availability is required. The engines are embedded with smart sensors, and the OEMs constantly monitor crucial parameters such as temperature, pressure, consumption, vibration etc. Sensor data is gathered and recorded onto a central server over a network to predict possible wear, estimate the components' useable life, and arrange a component repair or remanufacturing in a timely way (Yang et al., 2018). All in all, I4.0's primary benefit is its capacity to generate and access real-time information, enabling enhanced visibility and risk mitigation across the supply chain network (Fofou et al., 2021). Many of the I4.0 mentioned applications could potentially create value for stakeholders in the maritime industry, such as OEMs, ship owners/operators, shipyards and ship recyclers.

3.2.2. Internet of things (IoT)

With a simple definition, IoT refers to numerous physical devices that collect and share data. Small, widely dispersed, and practically linked ubiquitous sensors are at the heart of the IoT, which aims to continuously monitor individual objects and overall systems throughout their life (Tozanli et al., 2020b). From the CE aspect, IoT brings immense advantages to the table, such as remanufacturers being able to analyse used cores and linking physical conditions of the assets with sensor data, and ultimately able to interpret usage data to reach more accurate remanufacturing decisions. That will also improve the efficiency of remanufacturing operations.

In general, deciding the remanufacturing time depends on tracking the performance or physical/structural failures of "key components" over time and determining when the best time is to remanufacture the product (Fofou et al., 2021). To elaborate, a product comprises several components, some of which are "key components" owing to their significance for the whole product. By digitally keeping track of these critical components, smart systems can predict ideal remanufacturing timing. Some remanufacturing pioneers, such as Caterpillar, have been promoting customer condition monitoring services to control equipment costs, improve product performance, and reduce component failure risks (Caterpillar, nd).

3.2.3. Big data analytics & AI

Big data analytics is the application of sophisticated analytical methods to extensive, diversified data sets whose size or type exceeds the capacity of typical conventional databases to gather, manage, and analyse the data promptly. Big data has at least one of the following characteristics: a large volume, a rapid rate of change, or a great deal of diversity. Artificial intelligence (AI), mobile and social relationships and the IoT are increasing data complexity through new data formats and sources. For example, big data is created in real-time and on a massive scale by sensors, devices, video/audio, networks, log files, transactional applications, the web, and the social media (IBM, nd).

From the circular economy aspect, reverse logistics, cloud-based systems, and IoT can be combined, and big data can be utilised to interpret end-of-life decisions accurately.

3.2.4. Digital twins (DT)

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

By almost removing uncertainty about the state of returned end-of-life cores, DTs may play a crucial role in supporting rapid decision-making and planning in used component acquisition. OEMs may utilise predictive twins to estimate the remaining useable life of items based on data received via IoT infrastructure for product and component functionality. Predictive twins imitate the behaviour of assets or systems using historical data from their simulated real-time occurrences. The remaining service life of a product may be estimated using previous data collected from the product and its components, from other comparable devices, or a combination of these. Manufacturers may use this prediction model to forecast the future conditions of the full product and parts before proposing trade-in prices or offering remanufacturing services (Tozanli et al., 2020a). Fig. 2 depicts the pillars and potential benefits of

Fig. 2. Pillars and benefits of digital twins.

Digital Twins in remanufacturing, which can be employed by maritime OEMs as well. Besides OEMs, engineering consultancy firms, shipyards, or turn-key solution providers might consider generating the digital twin of a desired ship's engine room to maximise the utilisation of machinery and equipment there. By doing so, asset tracking would be substantially increased, meaning improved circularity metrics and remanufacturing opportunities.

3.2.5. Database and blockchain

Typically, a database is managed by a database management system (DBMS). Together, the data, the DBMS, and the programs that run on them are regarded as a database system, simplified as a database (Oracle, nd). To make processing and data querying as efficient as possible, data in today's most prevalent forms of databases is often structured in rows and columns in a sequence of tables. Thus, data may be easily accessed, managed, altered, updated, controlled, and organised. Most databases write and query data using the Structured Query Language (SQL) (Oracle, nd). If the system is complex and generates large amounts of -possibly live and diverse-data, it is classified under the Big Data section.

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

3.2.6. Smart recovery decision-making (SRDM)

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

Today's technological developments make more advanced solutions applicable, provided that all stakeholders are dedicated and in cooperation with each other.

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

- Continuously reporting smart on-board components equipped with sensors (IoT),

- Big Data analytics, analysing the vast amount of information gathered by IoT (Big Data),
- Blockchain technology to ensure higher database safety (BC),
- Digital Twins replicating both the vessel and onboard components' characteristics, enabling what-if experimental scenarios for maritime assets (DT),

Accurate EoL time and decommissioning value estimation for all marine assets by ML algorithms (AI).

- Component route estimation for EoL products by ML– i.e., whether to reuse, remanufacture or recycle as scrap,
- Accurate second-hand value estimation by ML for a vessel or single component at any time,

These technology solutions would pave the way for;

- Maximised EoL utilisation
- Optimised reverse supply chain performance
- Higher circularity & sustainability rates due to maximised remanufacturing.

4. Results

4.1. Maritime circular economy survey/questionnaire

Ship recyclers, OEMs, academia, designers, and engineering consultants are asked for their opinions on whether they see restorative circular economy principles such as reuse, remanufacture and repurposing as worthwhile efforts in the maritime industry for different parts and components on board marine vessels. The overall results indicate that they do, as seen in Table 1. Hydraulic components and complete engines are the most agreed-upon products, followed by engine parts and sub-components such as cylinder heads, engine blocks, turbochargers, crankshafts, and coolers. Therefore, the case study will focus on engine remanufacturing operations.

As for the manufacturer aspect, nearly two-thirds of the participants (63%) from maritime OEMs declare that they have adequate technical expertise and capabilities to perform CE principles and keep products (reuse-remanufacture and repurpose (RRR) end-of-life (EoL) engines and hydraulic components) in use for longer durations. The result clearly shows that remanufacturing know-how exists in the industry amongst OEMs. After discovering the ability to remanufacture-repurpose-refit valuable components in the industry, participants from academia and OEMs are further asked for their opinion and intentions towards RRR operations. 81.8% of them approved RRR operations and stated that they would prefer to carry it out, meaning there is a high willingness amongst researchers and manufacturers of the industry.

All things considered, it is safe to say that even though various barriers (e.g. low awareness, regulation difficulties, long lifecycle of vessels, geographic limitations and industry acceptance) exist within the sector (Okumus et al., 2022a), there is also considerable interest in circular economy applications for the parts and components listed in Table 1 within the maritime industry. Moreover, many maritime OEMs are eager and confident that they have the necessary expertise to carry out RRR operations. In the following sections, this research will focus on marine engines, as they are the most valuable components on board and given the expertise and interest from the OEM side. This paper will then cover some important strategies and technology solutions that might enable and accelerate the transition toward a more circular marine industry.

4.2. Marine engine remanufacturing process – a case study

The products in the transportation industries, such as automobile, aerospace/aircraft, shipbuilding, and railway sectors, are capital intensive, durable and designed with a relatively longer lifespan; remanufacturing in these industries is becoming more common (Fofou et al., 2021). Due to the products' extended lifecycles and high value, remanufacturing is the most cost-effective and appropriate recovery method at the end of life. This section will present engine remanufacturing along with a case study for the maritime industry.

Marine engine OEMs usually prefer a core deposit strategy to trigger a reverse supply of used components from customers to manufacturers. In the industry, core components flow is generally through the dealers, especially for the OEMs with broad service networks. On the other hand, some carry it out through their organisations in a more centralised structure. There are marine industry dealers who have improved their capabilities and capacities by collaborating with OEMs and making technological investments. Many ship owners or operators in the sector prefer rebuilding or remanufacturing applications carried out by those competent dealers, especially if they prefer their own components back in the same-as-new condition rather than exchange components.

Since the maritime industry is heavily regulated, marine engines go through a series of inspection and certification processes both in the design and manufacturing stages. According to International Association of Classification Societies (IACS) rules, each engine manufactured for marine application must have both a type-approval certificate and engine certificate. In order to carry out the aforementioned certification process, classification societies require a long list of documentation, including but not limited to technical drawings (e.g. engine cross-section, separate parts drawings, frame and bedplate welding etc.), assembly plans, production specifications for castings, engine control systems, starting-fuel-lubricating-cooling-hydraulic systems, safety systems, operation and service manuals and so on (IACS, 2022, Lloyd's Register, 2022).

Currently, there is no specific certification process or rules announced by the classification societies for the remanufacturing operation of engines. In the maritime stakeholder survey mentioned in Section 1.1, all participants from classification societies stated that in order to approve remanufactured components, OEM warranty and certifications are required, just like a newly manufactured product (Okumus et al., 2022b). Based on the information obtained from the literature and the OEMs examined in this section, a standard

Table 1
Whether the RRR efforts are worth it or not.

Whether RRR efforts worth it or not		Cylinders and other hydraulic components	Complete engine	Hydraulic pumps&motors	Cylinder heads	Engine block	Turbo–charger	Crankshaft	Engine coolers	Total
1	Strongly disagree	1	2	2	1	4	1	2	1	14
2	Disagree	1	0	2	2	0	3	3	3	14
3	Neither agree nor disagree	4	6	3	7	4	8	5	8	45
4	Agree	9	5	7	4	9	6	5	3	48
5	Strongly agree	7	8	7	6	4	3	4	4	43
	Mean	**3.91**	**3.81**	**3.71**	**3.60**	**3.43**	**3.33**	**3.32**	**3.32**	**3.56**

remanufacturing process is revealed for marine engines in Table 2.

In this case study, the rebuilding process of one of the main engines of a high-speed passenger ferry operating in Aegean Sea is examined. The engine was built in 2009, with 2300 RPM and 1450 HP. The vessel's maximum design speed is 30.9 knots, and two high-speed diesel main engines generate the propulsion power. The fleet manager of the vessel's owner company has sent the engines for rebuilding at around 9500 machine-hours, after their last overhauls, to the authorised dealer of the engine manufacturer in the region. The dealer has the capacity and capability to rebuild up to medium-sized marine engines.

In the preparation step, the dealer has conducted on-site controls and engine fluid analysis before removing the engine from the vessel. After remanufacturing approval was granted by the ship owner company, remanufacturing phases given in Table 2 were initiated. In the first phase, the dealer disassembled the engine in their rebuild centre while constantly checking for any failure traces. After that, all parts were cleaned, rust and paint removed.

In phase two, all the parts (such as the cylinder block, all galleries and holes, crankshaft, all bearings, journals, camshaft, pistons, piston pins, connecting rods, oil jets, cylinder cover, valve springs, rotocoils, liners, turbochargers, valve mechanism, oil pump, water pumps, gear bearings and so on) were inspected and evaluated. This is done according to the factory tolerance limits. Apart from wear and tear, curvature and shaft deflection measurements were also carried out. Depending on the part, tolerance limits in measurements varied between 0 and 0.15 mm which corresponds to ‰0.36 precision level. At the same time, the dealer carried out crack testing for all necessary parts. There was no required product upgrade for the engine since its last major overhaul. All measurements and findings such as scratches, cracks etc. were photographed and recorded.

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

In Phase III, the dealer restored all salvageable core parts within their capabilities (via machining, honing, polishing etc.) and reused them. However, some other parts were restorable with only the manufacturer's technical capabilities, so they were returned to the manufacturer to utilise once again. Finally, parts beyond recovery were sent to a metal recycling facility.

After reassembly, in Phase IV the engine was tested for rough operating conditions on a dynamometer at the dealer's engine testing facility. All metrics: pressures, temperatures, and engine performance-were monitored during the test, and leakage tests were carried out. With the participation of the customer's technical staff, the performance of the machine was recorded during the tests. The results were very close in terms of performance to its brand-new version. As shown in Table 3, the reman engine's performance is on par with its newly manufactured alternative.

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

After the remanufacturing process, the classification society of the vessel participated in the engine's reinstallation and recommissioning operations and carried out sea trials as well.

Considering test results and the overall remanufacturing process, the manufacturer allowed five year/8000 h extended warranty for the engine. Although extended warranty packages can be purchased, today, even a newly manufactured engine comes with a standard warranty of two years/unlimited hours. Brand new alternative of this particular engine also comes with two years and unlimited hours warranty coverage. Therefore, it is evident that both the manufacturer and dealer together stand behind remanufactured components and products, and so they go beyond standard warranty coverages. Fig. 3 show the before and after the dealer rebuild process.

4.3. Benefits of engine remanufacturing

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

From the CLSC perspective, the case presents a smart approach, that covers product acquisition, reverse logistics and flexible remanufacturing capabilities. First, the customer's awareness of remanufacturing has played a significant role in this case. Therefore, increasing awareness of the customers to have smoother product acquisition at the EoL is fundamental. Furthermore, as a result of OEM-dealer cooperation, the reman process was carried out at the dealer's facility, which tremendously reduced transportation cost and time of the core parts. In addition to that, the dealer's capacity and capabilities regarding remanufacturing operations is also valuable, and it has played an important role in the case study.

As an alternative scenario to this case study, a trade-in/take back strategy could be followed. In that case, the customer could directly purchase a remanufactured component (exchange component) without waiting for their engine, and the dealer would have sent all the cores back to the manufacturer. The customer would benefit from an economic advantage of remanufacturing all the same.

Table 2
Marine engine remanufacturing phases.

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

Table 3
The remanufactured engine's performance comparison with its new built factory test performance.

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

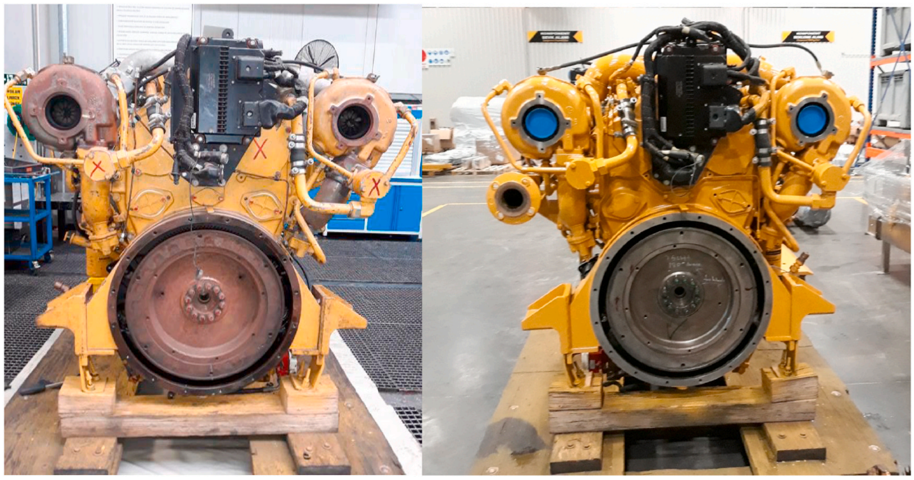

Fig. 3. Condition of the engine, before and after remanufacturing procedure.

From the technological aspect, the remanufactured engine is equipped with physical data collecting devices which enable condition monitoring services. Indeed, tracking the engine's operating statistics and fault codes might serve as a decision support tool for future recovery or EoL decisions, and ultimately it could lead to SRDM solutions when coupled with AI applications. Currently, there is a dedicated engineering team at the dealer company that focuses on condition monitoring and tries to optimise equipment utilisation including preventive maintenance, repairs and EoL solutions. The dealer, in this case, has established an extraordinary component rebuild centre; however, it is far from a mass-production plant. By its nature, rebuild operations are managed more like a job shop production system due to the diverse range of products and low volume per product model. Also, even though the dealer can restore most of the valuable parts of an engine, especially for smaller parts -such as injectors etc.- shipping them back to the manufacturer is more preferable. The reason is mainly economy of scale, and better technical capabilities in the manufacturer's remanufacture plants.

Several advantages of this case study are as follows:

- Heavier parts that can be remanufactured by the dealer, such as crankshaft and engine block, are remanufactured locally. So, there is a considerable saving in terms of logistic costs.
- The engine was sent to a local dealer's component rebuild centre rather than shipped to other countries or even an overseas facility.
- The local remanufacturing option attracted the customer. Their technical staff visited several times during the rebuilding process.
- Parts that were remanufacturable but replaced due to the customer's request were sent back to the OEM's remanufacturing facility.
- Parts found to be remanufacturable but needed beyond the dealer's capabilities were sent back to the OEM's remanufacturing facility.
- Ideally, in a dealer remanufacturing or rebuilding process, the parts to be replaced can be provided by the OEM's remanufactured part series. The engine or component would have been rebuilt by a combination of parts reconditioned by the dealer and parts remanufactured by the OEM. That means the engine would be 100% remanufactured. It is clear that by using reman spare parts, the dealer can rebuild the engine sustainably and circularly possible.
- However, due to import limitations for remanufactured parts by law in the dealer's country, they had to use new components for replacement rather than OEM remanufactured series.

4.4. Cost benefit analysis and comparison to brand new engine

Since the maintenance frequency and maintenance costs of both alternatives are the same, these costs are not included in the analysis. Moreover, as the performance of both alternatives is very similar, as shown in Table 3, they both generate the same benefit. Therefore, this section merely focused on present worth cost comparison. In the present worth comparison, disassembly/assembly labour, parts recovery costs, spare parts costs, consumable costs and fuel consumption differences have been taken into account. Moreover, the new engine and used/scrap values were also considered.

Even though it might simply originate from the sensitivity of the measuring equipment, the cost-benefit analysis was carried out considering the worst-case scenario. Therefore, a 0.6% difference in the fuel consumption given in Table 3 reflected a negative impact on the remanufactured engine as increased fuel consumption for ten years. Considering the ferry's operation profile, the engine will undergo a major overhaul in 7 years. However, for this analysis, the authors assumed it would take ten years just in case. After the major overhaul, the fuel consumption is expected to be the same for both alternatives – reman and new.

The scrap value is estimated according to current end-of-life used market prices, which takes salvaging it for spare parts into account. The annual interest rate of 1.25% is used according to European Central Bank's current fixed rate (ECB, 2022). The costs in Table 4 have been normalised according to confidentiality agreements.

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

$$PWC_{reman} = P + A * (P/A, 1.25\%, 10) \tag{1}$$

From Equation (1), $PWC_{reman,}$ the remanufactured engine costs slightly more than half of the new engine cost, by 51.7%. If the fuel consumption difference is neglected, considering the 0.6% difference can be caused by measuring equipment's precision, the cost ratio decreases to 44.2%.

5. Discussion and future perspectives

The maritime industry is facing a sustainability challenge, and some of these challenges can be addressed with a circularity transition. However, the industry's barriers are evident due to the supply chain, regulations, and the owners' perceptions.

This study investigated the potential options and demonstrated the

Table 4
Normalised cost of the remanufactured engine compared with the new engine.

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

benefits through a case study of remanufacturing. The maritime industry would only move towards the remanufactured items if the economic benefits were clear. This needs to be shown through further case studies of remanufacturing/refitting equipment on board existing and new ships.

Nevertheless, these solutions cannot benefit the industry without a proper take-up, which can only happen through incentives from policymakers and regulatory bodies. The barriers preventing the use of second-hand or remanufactured items must be removed for the sake of the industry and to achieve actual sustainability within the sector. Policymakers should also consider further benefits such as tax breaks for remanufactured items or schemes to encourage their use. A further study investigating the potential incentives and their impacts are needed to demonstrate these clear benefits to all stakeholders.

In addition to these actions, the maritime industry also needs to improve the "reverse supply chain" part. At the moment, the end-of-life vessels end up a thousand miles away from their "home" or birthplace, making collecting these items almost impossible. To successfully implement this concept, hubs for the circular economy must be considered. The UK can become one of the hubs to combine the know-how in the remanufacturing operations with practical applications to create financial and social benefits. Other candidates for these operations can be Germany (manufacturing advancement), Turkey (shipyards-new build-repair and recycling are heavily located), and Indonesia (excellent location in the middle of world trade routes). Further investigation of this opportunity will be done in the future.

Moreover, the characteristics of the industry (such as the wide range of materials on board or the long-life cycle) make the software and hardware solutions "a must". Therefore, the applications of the potential solutions identified as part of this study should be investigated in further case studies and developed further to be used by the industry.

6. Conclusion

In conclusion, this study has demonstrated that the maritime industry is way behind the other transportation industries. This study demonstrated the current knowledge and approach of the maritime industry through a survey study to find out the existing knowledge and perception. This study also reached out to over 80 people from different backgrounds within the marine industry to paint an accurate picture of the industry.

Following the questionnaire findings and the solution investigations, a case study demonstrates the remanufacturing capabilities and the opportunities. The authors hope that this case study will prove to the maritime sector the exquisite care that remanufacturing businesses put into reman engines, as well as the economic, warranty, and corporate social responsibility benefits.

Moreover, the potential applications for the maritime industry in terms of strategy, software and hardware solutions have been investigated and presented for the industry. The authors believe the industry can benefit from this application investigation as a guide to circularity transition, which will support the sustainability of the maritime industry. However, the sector's massive sustainability potential will be wasted without industry-wide action. Especially in the UK, strong collaboration links are required to create expertise within this area and pioneer the developments within the area. Although the UK has set its goal towards net zero, the maritime industry only sees these goals as operational change but not as a supply chain or manufacturing. Therefore, to create this awareness, industry-wide campaigns are necessary.

CRediT authorship contribution statement

Dogancan Okumus: Methodology, Investigation, Formal analysis, Data curation, Writing – original draft. **Sefer A. Gunbeyaz:** Conceptualization, Formal analysis, Supervision, Funding acquisition, Writing – original draft. **Rafet Emek Kurt:** Validation, Writing – review & editing. **Osman Turan:** Writing – review & editing, 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.

Data availability

Data will be made available on request.

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