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Critical success factors for remanufacturing and reuse of equipment in the engineer-to-order shipbuilding industry

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ABSTRACT

Ship equipment is of extremely high value, making them prime products for remanufacturing and reuse. However, despite increasing efforts to regulate the impact of shipping on the environment by promoting circularity, the strategies extending the product life of marine equipment, especially in European shipbuilding, are limited. This paper aims to identify critical success factors that enable better decisions making for remanufacturing and reuse of equipment in the engineer-to-order (ETO) shipbuilding industry. It contributes with an empirical study addressing circularity in the maritime industry for ETO products, which are typically designed for a specific customer. The research is based on an inductive study incorporating multiple workshops within the Norwegian ship building industry and includes actors such as original equipment manufacturers (OEM), shipyards, ship operators, and a classification society. The type of equipment in focus includes thrusters, cranes, generator sets, and hydraulic power units. Critical success factors specific to shipbuilding remanufacturing and reuse are identified, which are compared and contrasted with existing generic factors from the literature. We also examine the potential tensions and areas of agreement between the actors in the supply chain in relation to the identified factors. Our results confirm the potential for interfirm tensions, indicating that tensions in terms of perceived levels of importance exist in relation to damage, transport, product types, product value, and material composition. The study proposes self-reflective managerial questions, as well as new research lines to undertake a whole systems evaluation of the opportunities for adopting remanufacturing and reuse in the shipbuilding supply chain.

1. Introduction

Engineer-to-order (ETO) products are customised, i.e. they are engineered and produced for specific projects and customers' requirements. This implies high numbers of engineering hours and a significant level of unique and high-value materials, components, and solutions. As a maritime product, vessels from shipbuilders comprise a substantial proportion of engineered equipment and components, allowing them to be identified as ETO products (Mello and Strandhagen, 2011). From the perspective of operations and supply chain management, producing a ship requires thousands of engineering hours. The sector is known for its high level of complexity and advanced operations (Willner et al., 2016; Nam et al., 2018; Strandhagen et al., 2022), along with the production of ETO equipment that has significant remanufacturing and reuse potential (Okumus et al., 2023b; Søyland and Bishop, 2024). The equipment is of high quality, holds significant value, and is durable, thus retaining a residual value at the end of its use. Access to used equipment is substantial, as over 50 % of the world's fleet is more than 15 years old, and the number of decommissioned ships is steadily increasing (United Nations, 2024).

In line with the need for a green transition and decarbonisation in the shipping industry (Agarwala, 2023), access to equipment for remanufacturing and reuse offers a significant opportunity to reduce the shipping industry's carbon footprint and enhance its environmental sustainability by decreasing the demand for new materials and extending the lifespan of vessels. Moreover, remanufactured equipment improves supply chain resilience by ensuring availability during times of supply disruptions or material shortages, and it reduces costs.

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Additionally, many mid-life ships must undergo remanufacturing to meet newly implemented environmental and technological standards (Daniel and Lee, 2022), which make the equipment a good candidate for scaling up the circular economy.

According to a recent European study, the maritime sector has the lowest intensity within the EU's remanufacturing activities, indicating its lack of presence in such operations (Parker et al., 2015; Milios et al., 2019), although there are some industry examples where companies claim to be trialling remanufacturing (e.g. AEGIR-Marine, 2023). Compared to other industries, e.g. aerospace, automotive and rail, the scale of remanufacturing in the shipping industry is low (Wahab et al., 2018; Milios et al., 2019). Okumus et al. (2023b) see this as the result of weak incentives and directives from national and international regulatory bodies, although this is changing with the launch of the EU's Corporate Sustainability Reporting Directive (CSRD) (European Union, 2022). Without external regulatory stimuli or nudges, the adoption of circular business models is unlikely to occur, because it may cannibalise existing operations – thus reflecting the "innovator's dilemma" (Kuhlmann et al., 2023). Companies face significant challenges in coordinating efforts to establish circular supply chains (Aspelund et al., 2021), despite a broad consensus on the benefits of circular practices and the introduction of new regulations such as the CSRD.

Although there are currently extremely limited documented examples of remanufacturing in the shipbuilding industry, a notable exception is that of Okumus et al. (2023a) who highlight the value of remanufacturing ship engines, where an extended warranty of five years is offered by the engine manufacturer. Following this, important decisions must be made regarding remanufacturing and reuse options in the end-of-life (EOL) phase of ship equipment. A number of factors are essential for understanding how to extend equipment life and, ultimately, to make decisions that contribute to circular practices (Alcaide et al., 2017; Strandhagen et al., 2022). There is published research on generic factors, for example, Singhal et al. (2020) who undertake a deductive approach to develop a generic model of success factors with some limited testing with seven academic 'specialists' and four practitioner 'experts' of unknown detailed background, Werner-Lewandowska et al. (2025) who also take a deductive method to develop a conceptual model of factors based on existing literature (including Singhal et al., 2020), in terms of barriers and enablers, and tested with just five 'experts' from the electrical and electronic sector, and Ziout et al. (2014), who employ a deductive approach to determine factors that are then tested via a single illustrative case study from the automotive fuel cell industry. To the best of our knowledge, there is very little research in shipbuilding. Of the existing studies on remanufacturing factors, none consider the tensions that may exist across different supply actors who have different perceptions on some of the factors underpinning remanufacturing decisions.

This study addresses the underpinning factors that determine whether reuse or remanufacturing is feasible. Several studies, for instance, Werner-Lewandowska et al. (2025), Singhal et al. (2020) and Ziout et al. (2014), have developed broad categories of remanufacturing success factors emphasising strategic, policy and business model-related factors. This study builds on such studies in the context of ETO shipbuilding operational factors, and we ask what the critical success factors for remanufacturing and reuse are in this area. To identify the challenges and opportunities, we also explore the potential tensions and differences or agreements in perceptions of success factors among various stakeholders in the supply chain, since there may be a divergence, for instance, between the shipyard and an equipment supplier. Therefore, *the aim of this paper is to identify critical success factors for remanufacturing and reuse of equipment in engineer-to-order (ETO) shipbuilding supply chains and to determine if there are any tensions between different supply chain actors*. The following research questions are posed:

1. What are the critical success factors for the adoption of remanufacturing and reuse in shipbuilding supply chains?
2. What is the relative importance of such factors?
3. How do such shipbuilding industry factors and their importance compare with generic and/or other industry factors identified in the literature?
4. How are the critical success factors perceived by individual actors in the shipbuilding supply chain?

Through an inductive study, this paper explores the drivers and barriers to deploying remanufacturing and reuse strategies for EOL ship equipment. Multiple workshops were held within the Norwegian shipbuilding industry, including original equipment manufacturers (OEMs), shipyards, ship operators, and a classification society. The type of equipment in focus includes thrusters, cranes, hydraulic power systems, and generator sets. The identified critical success factors for remanufacturing and reuse are compared and contrasted with existing generic factors from the literature, and discussed in relation to current circular maritime literature. While several existing success factors are identified, others are not, and new ones are proposed. The contribution of the study is that it is the first to look at critical success factors specifically for the shipbuilding industry, where others have looked at such factors generally or in other industry contexts. We then contribute to the general body of knowledge on critical success factors for remanufacturing by confirming existing factors as well as by adding new ones. Also, unlike other studies, we examine the potential tensions between the actors in the supply chain for each category of identified factors.

The rest of the paper is organised as follows. Section 2 gives a background on the existing literature on circularity in the maritime sector. It then provides an overview of existing generic knowledge on the critical success factors related to the adoption of circular economy and the tensions that may arise when trying to achieve circularity. It should be noted that, although we present the factors and tensions in Section 2, our study is inductive and hence the general literature on critical success factors and tensions was not reviewed until after the empirical data collection and analysis had been performed. Section 3 details our research method, and Section 4 presents the results of our empirical findings. In Section 5 we close the loop back to the existing literature to determine which critical success factors are similar to those that have been previously established and which are novel in this study. We then conclude in Section 6 by highlighting the substantive outcomes of this study and discussing its implications for future research and practice.

2. Background

2.1. Remanufacturing and reuse of equipment in shipbuilding

Circular strategies in the shipbuilding industry are well established, although mostly by practising recycling of steel and other metal or non-metal materials into new products (Ocampo and Pereira, 2019). The dominant part of the recycling industry is in South Asia in countries such as India, Bangladesh, Pakistan, Turkey, and China, even though most of the ship fleet for recycling comes from North and South America and Europe. Shipyards in the Asian region annually recycle between 800 and 1400 ships, which in 2016 was 96.6 % of the total market (Ocampo and Pereira, 2019).

When circular strategies in the shipbuilding industries primarily target large material and metal groups, such as shipbreaking, they risk downscaling material value and diminishing the worth of ETO equipment and components. Although, recycling large material groups facilitates material recovery, it does not preserve durable cores for reuse in subsequent life cycles, thus limiting the potential to reduce the demand for new virgin materials. However, recycling mainly contributes to saving energy and carbon emissions rather than maintaining the properties of a product (Milios et al., 2019). Thus, for ETO equipment, that are capital-intensive and durable, alternative restorative strategies such as remanufacturing and reuse are considered to have a circular potential. By upscaling and prolonging the value of the equipment and delaying the stage of recycling, these strategies postpone the need for recycling making them a more material efficient approach compared to immediate recycling (Wahab et al., 2018; Milios et al., 2019; Okumus et al., 2023a; Scipioni et al., 2023). Remanufacturing is an industrial process that turns used equipment into equipment with the same quality, functionality, and warranty as new equipment, effectively giving it properties equal to new equipment (Milios et al., 2019). In contrast, reuse is considered as any operations by which equipment that is not classified as waste are used again for its original purpose, including practices such as reuse, resale, repair, refurbishment, and reconditioning (Milios et al., 2019).

Another consideration is the quality of returns for remanufacturing. The lower the quality grading of a return then the potential increase in remanufacturing costs, equipment degradation, energy use and emissions (Liu et al., 2025). But there is also potentially an upside with lower grade returns for remanufacturing in what is known as the "quality paradox" where, due to higher remanufacturing lead-time requirements, lower-grade returns can potentially enhance customer service levels via improved inventory dynamics (Ponte et al., 2021).

One reason for this low intensity of ETO equipment is that selecting equipment for remanufacturing or reuse is a multi-criteria decision affected by factors related to engineering, business, environment, and society (Ziout et al., 2014). The selection is even more complicated in shipbuilding compared to other industries because of the ETO dimension, which means that vessels, especially European vessels, are one-of-a-kind, tightly integrated, capital-intensive, and complex products. Different types of main equipment are engineered to be installed at a particular location on the vessel, to have specific dimensions, and to have functionality and performance that are optimised for the vessel's purpose. Finding and redistributing suitable used equipment to install on a vessel is often more challenging than buying new equipment because logistics are complicated, costs are high, and the maturity of markets is low. Therefore, much of the used equipment is either disposed of or recycled together with the hull and other steel components of the ship. The main challenge seems to be understanding when remanufactured or refurbished equipment can be installed on a vessel instead of new equipment.

Equipment from the maritime industry, that are particularly appropriate for remanufacturing and reuse purposes, are capital-intensive and durable products designed to have a relatively long lifespan. Okumus et al. (2023a) have shown that most of the equipment in the engine room of a conventional merchant ship or a pleasure craft are good candidates for remanufacturing and reuse. Typical ETO equipment includes cylinders and other hydraulic components, hydraulic pumps and motors, engines, cylinder heads, engine blocks, turbochargers, crankshafts, and engine coolers (Jansson, 2016; Okumus et al., 2023a). The high value and long-life cycle make them cost-effective to remanufacture, as shown in a cost-benefit analysis by Okumus et al. (2023a). Interestingly, because ETO ship equipment is well documented and registered, such as type-approval certificates, technical drawings, assembly plans, production specifications, control systems, safety systems, operation and service manuals, and so on, this makes them traceable and attractive as tradable in a circular marked (Okumus et al., 2023a).

To increase the level of remanufacturing and reuse of ship equipment, recent studies argue for system-wide interventions such as new economically viable business models securing the supply and demand of used equipment, circular and reverse logistics infrastructure (hubs), supporting technological information systems, skills and competence, incentives from policymakers, and regulatory actions (Milios et al., 2019; Okumus et al., 2023a).

A professionalised take-back system needs to be developed to support the complex system of operations needed for the remanufacturing and reuse of ship equipment. There is a potential for OEMs and third-party remanufacturers to be a key stakeholders (Okumus et al., 2023a) in collaborative networks of ship owners, ship yards, and classification bodies. However, previous studies have shown that coordination and alignment across the type of complex ETO supply chains found in shipbuilding may involve integrating very different worldviews and risks (Mello et al., 2017; Alfnes et al., 2021). Thus, a deeper understanding of any points of departure and agreement is needed to better understand the factors, possibilities, and barriers for remanufacturing of ship equipment.

2.2. Factors impacting remanufacturing and reuse

In this section, we investigate the existing generic circular studies and maritime studies that might be relevant for selecting equipment for remanufacturing or reuse before installation on another vessel and to identify factors and categories. To understand how to increase circular and restorative strategies, there is a need for insights into the barriers, drivers, and success factors for the transition to such strategies. Not all strategies are suitable for every used product, and factors such as product characteristics and design are crucial in determining the feasibility and potential for implementing circular strategies (Russell and Nasr, 2023). A growing circular awareness is emerging both for generic and context-specific barriers and resistance, motivation, and success factors for remanufacturing and reuse product strategies. Table 1 shows the substantive studies that have explored critical success factors. Although Okumus et al. (2023a) is not one of the studies, we have included it as the only paper we have identified that specifically examines remanufacturing in the shipbuilding industry, albeit through a limited Likert-scale questionnaire and an illustrative single case study.

A range of generic studies provide insights about critical factors in the remanufacturing and reuse of products in industries such as aerospace, automotive and railway. According to Singhal et al. (2020), remanufacturing is especially promising because it is the only circular business model that provides the lates features and warranties for the product. Singhal et al. (2020) identified and ranked a list of critical factors that have a significant influence on remanufacturing. Their focus was on critical success factors for remanufacturing business models, and the majority of their 19 factors were within the business and societal dimensions. They only identified two factors related to engineering, i.e. "design for remanufacturing" and "technology". Their study revealed that design for manufacturing, collection strategy, management prescience, purchase intention, and the identity of the remanufacturer are the factors that impact remanufacturing most. In addition, Bhatia et al. (2022) and Singh et al. (2023), identified success factors that enable circular economy principles. Both studies suggested that top management decision making is a key factor.

Some maritime studies have contributed to insights about barriers to and the potential for remanufacturing and reuse of ship equipment from literature reviews and empirical studies (surveys and rich case studies). Okumus et al. (2023b) argue that circularity is hindered by a lack of stimuli from regulatory bodies and a lack of systems for reverse logistics, and they suggest that hubs aggregating manufacturing operations and digital information technology could motivate OEM to establish viable business models. Similar conclusions come from a study by Milios et al. (2019), but that study also emphasised that issues related to costs, competence and waste collection infrastructure also need to be addressed. Wahab et al. (2018) analysed the design aspects for remanufacturing and argue that even if design changes and innovation will increase costs, products could be offered at prices that are competitive with newly manufactured products without lowering quality. However, none of the maritime studies specifically explored the critical success factors related to the products and the production and engineering aspects related to remanufacturing and reuse, but instead mainly focused on the strategic and managerial aspects of barriers and prospects for circularity.

Some generic manufacturing studies provide insights into technical and operational aspects of remanufacturing and reuse of products. Nasr and Thurston (2006) argue that product remanufacturing strategies

Table 1
Comparison of academic studies relating to success factors for remanufacturing.

Study	Summary/Relevant findings	Methodology adopted	Commentary
Ansari et al. (2019)	- Identified 32 common critical success factors for adopting remanufacturing practices in supply chains. They developed six high-level categories: managerial, strategic, regularity, technological and infrastructural, financial, and social.	- Critical success factors were identified from the literature and analysed via Fuzzy Analytic Hierarchy Process (i.e. this was a **deductive** study)	- Tested across industries in India, although none were identified as maritime/ shipbuilding. - This work offers general critical success factors, as opposed to being specific to shipbuilding.
Bhatia et al. (2022)	- Identified 21 high-level strategic factors. - Green innovation was identified was the most critical, followed by management support and coordination, design for recovery, and managing product returns.	- **Deductive** study, based on the existing literature, that performed a survey using a Likert scale questionnaire, targeting manufacturing Small and Medium-sized Enterprises (SMEs).	- Used an external data collection firm with various industry sectors, but none were identified as maritime/shipbuilding. - The results were related to closed-loop supply chains, rather than specifically to remanufacturing.
Okumus et al. (2023a)	- Focused on identifying suitable strategies and technology solutions for the maritime industry. - Strategies included recovery hubs, seeding, takeback strategies, product service solutions, and software solutions.	- **Deductive** based questionnaire with 83 participants, followed by a single case study.	- This was a maritime-specific study and demonstrated implementation of solutions in the context of marine engine remanufacturing. - Identified useful strategies for remanufacturing, but not the success factors.
Singh et al. (2023)	- Identified 15 high-level strategic critical factors. - The most influential factors were identified as top management participation, market for recovered products, and the promotion of circular economy-oriented R&D activities.	- **Deductive-**based approach was used, exploring the literature for success factors and subsequently confirming them through a 'grey' Delphi study and weighted aggregated sum/product assessment.	- Ambiguous as to who were the experts used for the Delphi study with no industry background given except that they had "over twelve years of managerial experience in the area of circular economy and sustainable supply chain".
Singhal et al. (2020)	- Identified and evaluated the critical factors with a significant influence on remanufacturing. - Identified 19 success factors and found that design for manufacturing, collection strategy, management prescience, and purchase intention were the top factors.	- **Deductive** method where the literature was used to develop a questionnaire using Likert scales and the Fuzzy DEMATEL method.	- Success factors generated from literature were identified and then tested across industries, but none were identified as maritime/ shipbuilding. - Provided a useful generic list of remanufacturing success factors, but not specific to maritime/shipbuilding.
Werner-Lewandowska et al. (2025)	- Identified and evaluated factors by which the circular economy may be enabled or restricted via remanufacturing. - Identified 30 factors and their interrelationship where 12 were enablers of which the "Right to Repair" regulation was the most influential	- **Deductive** method where the literature was used to develop a conceptual model and tested using Likert scales and the Grey DEMATEL method.	- Generic factors generated from literature were identified and then tested across the electrical and electronic industry but no further detail of sub-industries e.g. automotive, personal computers or shipyards.
Wuni (2023)	- Identified 51 critical success factors for circular construction projects, clustered into six typologies: technological, supply chain, organizational, stakeholder success, and management success factors.	- Systematic review of critical success factors (i. e. **deductive**) for circular economy implementation in construction projects.	- Construction-sector oriented, rather than maritime/shipbuilding specific. - Provided a comprehensive list of factors on how best to implement circular economy principles in construction projects.
Ziout et al. (2014)	- Investigated closed-loop product life cycle phases and recovery options. - Presented a multi-criteria decision-making tool for end-of-life recovery options. - Most comprehensive in terms of the number of factors with 71 identified. - Included factors at the higher level of the hierarchy including engineering, business, environmental, and societal factors.	- **Deductive** study, constructing a hierarchical decision-making matrix. - Tested via a single illustrative case study regarding automotive fuel cell remanufacturing.	- Useful hierarchical success factor framework for comparison that tended towards operational factors rather than just strategic factors, given the deep dive of the case study. - The matrix was generic and was tested in the automotive sector. - Broad coverage using PESTEL.
This Study	As per sections 4 & 5, we confirm existing critical success factors as well as suggests new ones, although with a more operational than strategic perspective. While we rank the factors, we go one step further and also identify tensions between supply chain actors, which is something that none of the above studies have done.	See Section 3. In contrast to all the previous studies, we undertake an **inductive** approach and use a qualitative workshop method that is commensurate with such an approach, hence balancing breadth with depth.	- Specifically tailored for maritime and shipbuilding equipment. - Empirically grounded. - Supply chain perspective, acknowledging potential tensions across different organisational perspectives.

should be decided based on the criteria of value and the cost of the component, the technical feasibility of remanufacturing, the economic feasibility of remanufacturing, disposal options and environmental impacts. These criteria are supported by Lund and Hauser (2010) but also expand our understanding to include more specific technical and product criteria (the availability of restoration technology without component damage, products composed of standard interchangeable parts, and cost-effectiveness where the used product's low cost outweighs any loss of functionality) as well as market and business incentives and, environmental and societal criteria. Finally, Ansari et al. (2019) developed an extensive, and prioritised, list of general critical success factors to be considered for adoption across a supply chain.

The most relevant framework to analyse our findings was developed by Ziout et al. (2014), and we use their framework for analysing EOL recovery options to structure, compare and contrast our findings. Ziout et al. (2014) performed a literature study to identify and categorise the factors related to restorative decisions. Their study took a holistic approach, so the identified factors are relevant for all of the broad dimensions of the PESTEL framework and can be used to develop multi-criteria decisions, that take into consideration different stakeholders' perspectives, for restoration, including reuse, remanufacturing, recycling and disposal. Their method was tested through a single case of product recovery decisions making in the automotive industry. Such a high volume, low customisation sector provides an interesting contrast with the low volume, high customisation ETO shipbuilding industry. The main categories influencing EOL decision making included engineering factors, business factors, environmental factors and societal factors (Ziout et al., 2014). In section 5, we undertake a deeper dive into these categories and present the specific critical success factors by comparing and contrasting our findings with those of Ziout et al. (2014).

2.3. Tensions in achieving circularity

Ziout et al.'s (2014) substantive motivation for the development of a multi-criteria decision-making tool was the need to consolidate the varying and sometimes conflicting perspectives of different stakeholders in establishing a sustainable business model. Such tensions have been documented by other researchers who realised the need for intra-resource, inter-resource, intra-firm and inter-firm trade-off considerations (Manzhynski and Figge, 2020). For this study we only considered the latter, which have implications for structural tensions, that is, due consideration of supply chain relationships and power dynamics, but these may also have implications for firm's psychological and behavioural aspects (Dagilienė and Varaniūtė, 2023).

There is a suggestion that the choice of the final business model ultimately leads to a compromise solution requiring a give and take between sustainability goals and economic value (Stål et al., 2022). Schultz (2022), building on Epstein et al. (2015), argues that such trade-offs may result in a win-win situation when considering the boundary conditions set by the decision makers, i.e. the establishment of a social and environmental 'red-line' that should not be crossed.

Oskam et al. (2021) observed in private and public sector cases that tensions arise among stakeholders even when there is a desire for a collaborative approach to creating a circular economy model. They suggest that these tensions can be overcome via two approaches, namely, collective orchestration and collective search. The former requires the establishment of clear and shared vision and goals for the establishment of the sustainable business model, to which all subsequent activities are judged, while the latter explores the establishment of relationships with new actors and there is a continuous adaptation of what the sustainable value proposition is. The collective orchestration approach is akin to that promoted by Tschiedel et al. (2024) that requires a collective approach to defining agreed-upon aims and establish mutual trust at an early timepoint in the transition to circularity. When such tensions cannot be overcome by the stakeholders themselves then government intervention by legislation is required (Xiong et al., 2016).

3. Method

We adopted an inductive approach, exploring the empirical phenomenon in terms of the extent to which the shipbuilding industry is adopting circular economy strategies and were identifying the critical success factors, i.e. opportunities and challenges, associated with their adoption. Exploiting a qualitative approach often associated with inductive research, we undertook workshops with different actors in the ETO shipbuilding supply chain. The purpose of our inductive method was to identify critical success factors in the collected data and to determine whether some potential new general rules, laws and/or theories might emerge for future testing (Glaser, 2001), which is important because no existing frameworks are focused on the maritime/shipbuilding industries. The overarching research design took a case-based approach, using workshops with participants related to each case as the primary form of data collection, and thus a total of nine workshops were undertaken.

We not only looked for commonality between the various stakeholders' perspectives but also looked for any potential tensions that might arise. We tested whether the emergent outcomes of the research had previously been identified more widely by comparing and contrasting our findings with existing generic factors from the circular economy literature (e.g. Ziout et al., 2014), and this also allowed us to position our findings within the general body of knowledge (Glaser, 2001).

Our overall approach was appropriate for several reasons. Because circular economy strategies in the maritime sector are under-researched in academia (Milios et al., 2019), an exploratory study could be beneficial for gaining new insights into the phenomenon. Furthermore, the regulation of remanufacturing varies by industry. The exploratory and inductive nature of our study enabled us to identify business and policy challenges that are specific to the maritime sector (Milios et al., 2019).

3.1. Case selection

The companies selected represent the substantive actors in the Norwegian ETO shipbuilding industry, covering shipowners, shipyards, equipment manufacturers and service providers (Jakobsen, 2011). Given the highly regulated environment, we included the latter as a classification society rather than as a direct constituent of the supply chain.

Our focus was on the potential for the remanufacturing and reuse of ship equipment, and we investigated equipment on deck, in the engine room, and for propulsion. We depict the resulting supply chain in Fig. 1 with the ETO characteristics of the companies given in Table 2. We included four equipment manufacturers, and two owners and operators of ships. We also included two shipyards, where one specialises in new builds with some conversion work while the other, although also involved in new builds, provides a dismantling service that the first does not. Finally, the classification society represents the wider regulatory environment that the other companies in the (closed loop) supply chain reside in. Most of the companies (A-F) had existing or previous relationships with the authors, but new ones were identified (G-I) via snowballing based on recommendations from these previous contacts. The main criteria were that companies were active in the circular economy, thus ensuring that there were no gaps in Fig. 1.

(A) is a leading manufacturer of propulsion systems and thrusters for a wide range of vessels, including ships, offshore installations, and aquaculture facilities. The products are designed to last the same lifespan as the ships they are installed on, which is typically around 25 years. (A) has a global service team and offers an aftermarket service program that includes spare parts, onboard services and maintenance, as well as upgrade and retrofits at their plant.

(B) is a globally recognised equipment supplier specialising in advanced handling and lifting solutions for the maritime industry. Their products include cranes, winches, launch and recovery systems, and various handling systems. (B) has a global services and upgrades team and offers an aftermarket service program that includes spare parts, service, maintenance, upgrades, and retrofits of the vessel on-site.

(C) is a supplier of propulsion engines, auxiliary engines, and generator systems to the maritime industry. Aftermarket services are an important part of their business. Repair and maintenance services account for two thirds of their service revenue, while remanufacturing/refurbishing at their workshop contributes the remaining third of their aftermarket business.

(D) is Norway's leading dealer and manufacturer of hydraulic equipment, and provides accumulators, cylinders and power units for all types of vessels. Their aftermarket business is split evenly between repair and maintenance services, and remanufacturing/refurbishing carried out in their own workshop.

(E) is a shipyard with a long history of designing and building innovative ships for various industries, including offshore oil and gas, fisheries, and renewable energy. The company offers expertise in design, engineering, project management, construction, installation, and commissioning. (E) execute newbuild and aftermarket projects, including conversions, retrofits, maintenance, and after-sales services. It also plays a role in the remanufacturing of onboard equipment and

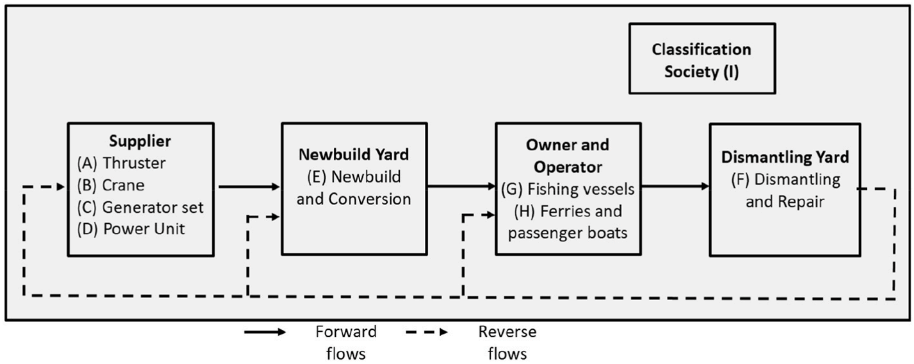

Fig. 1. The studied closed-loop supply chain and its substantive actors.

Table 2
Case companies.

Company	Volume (quantity per year)	Duration (weeks)	Cost per unit (€ '000s)	Engineering hours (per unit)	Workshop Participants
A Supplier Thruster	200–300	11–50	101–1000	101–1000	Chief Operating Officer, VP Process & Production Engineering
B Supplier Crane	900	51–100	1000	8000	Manufacturing Network Manager
C Supplier Generator set	100–200	11–50	101–1000	100–250	Service Director, Head of Repair Department
D Supplier Hydraulic Power Unit	200	11–50	11–100	101–1000	VP Service and Aftermarket, Team Leader Service and Aftermarket
E Yard - Newbuild and Conversion	20–25	11–50	1001 - 10 000	10 000	Managing Director, Senior Sustainability and Marketing Consultant
F Yard - Dismantling and Repair	10–20	12–24	1000–2000	101–1000	Sales Manager Retrofit, Senior Project Purchaser
G Ship Owner and Operator - Fishing vessels	1–10	51–100	101–1000	1001 - 10 000	Operations Manager
H Ship Owner and Operator - Ferries and passenger boats	0–1	11–50	1001 - 10 000	Unknown	Chief Technology Officer, Technical Inspector
I Classification Society	Not applicable	Not applicable	Not applicable	Not applicable	Business Lead (Maritime), Work Process Manager

serves as a key link between shipping operators and maritime equipment suppliers.

(F) is a prominent shipyard operating as a life cycle shipyard, offering comprehensive solutions in the maritime industry. With expertise in new builds, ship recirculation, and ship remanufacturing, the company provides various services such as construction, repairs, rebuilding, and recycling of vessels. (F)'s commitment to environmental management and quality assurance is evidenced by their ISO certifications, ensuring adherence to rigorous quality and sustainable practice standards.

(G) is a shipping company that primarily focuses on its own fleet's operation and maintenance. The fleet includes six vessels, with three actively deployed for fishing operations. The company engages in the distribution of various products, including fish and shellfish. (G) possesses a mechanical workshop, warehouse, and sandblasting hall. The mechanical workshop plays a crucial role in maintaining the main vessels' operational efficiency, with any surplus capacity utilized for other boat remanufacturing projects. Given (G)'s extensive expertise in remanufacturing ships and maritime components, it is well-positioned to offer valuable insights from a shipowner's standpoint.

(H) is a shipping company with approximately 90 vessels that provide ferry connections and high-speed passenger boat connections. The lifetime of their ferries is 50 years, which is longer than other types of maritime vessels. A typical contract for a ferry or boat connection has a duration of 10 years. New contracts for public transport in Norway, and especially ferries, require the replacement of fossil fuels with electricity as the primary source of energy. (H) typically has one vessel conversion project every other year, but the volume fluctuates depending on the market situation.

(I) has established a significant presence in the maritime industry, offering a broad spectrum of services to facilitate safe and efficient operations at sea. Among their principal activities in this industry are the classification and certification of ships, offshore platforms, and other maritime products, in addition to providing advisory services concerning risk management, design and engineering, and regulatory compliance. Through their classification services, (I) assists shipowners and operators in guaranteeing that their vessels satisfy international safety and environmental standards and are appropriate for their intended application. Understanding classification societies such as (I)'s perspective on the matter provides us with a broader understanding of the challenges that other companies face through their standards and requirements.

3.2. Data collection

Data collection was performed in two stages; the first was a series of workshops with key personnel from each company, and the second was a series of follow-ups interviews. Participants were identified as knowledgeable informants with an understanding of the depth and breadth of a company's operations and with an appreciation of the subject matter of the research, e.g. the factors that need to be considered when deciding if it is worth it to remanufacture or reuse thrusters and cranes? A semi-structured protocol to provide flexibility in workshop discussions, enabling the development of ideas and questions that were more widely related to the research topics. This approach also allowed substantive issues to emerge (Glaser and Holton, 2007; Denscombe, 2017). Two authors were present at the workshops, which were led by one of them and followed a guided structure.

The guide, as shown in Appendix A, was sent ahead of time so that the participants could read about the relevant information and get an insight into what was set to be discussed in the workshops so that they could prepare if necessary. This included a section related to the company details, another section on the supply chain, and a section related to remanufacturing/refurbishment. The guide also included a set of predetermined open-ended questions used as a base, with additional questions which resembled a dialogical approach. The questions were used to promote discussion while retaining a focus on the subject at hand.

Each workshop began with a presentation by one of the authors, highlighting the aim of the research and articulating some top-level models and principles of closed-loop supply chains. Each participant was then asked to identify potential products they believed to be remanufacturable, followed by a discussion on the drivers and barriers to their remanufacturing. This process helped establish a foundation for a better understanding the remanufacturing business before addressing the main topic, which was the critical factors for remanufacturing and reuse recovery options. After each workshop, a transcript of the answers to the predetermined questions was sent for verification. The participants were asked to review the statements and to give feedback if something was incorrectly interpreted, thus ensuring the robustness of our final findings.

After all nine workshops were finished, the authors synthesised all factors into a finalised list. This final list of factors was then sent to participants with follow-up interviews for validation, to reflect on any further success factors and rank them in terms of their of importance. Each participant was asked to rate each factor on a scale of 1–5, where 5 was most important and 1 was the least important.

3.3. Data analysis method

We first undertook a simple summation, sum_i, of each company's critical success factor score, $score_i$, to determine their relative rankings i.e.

$$sum_i = \sum_{i=1}^{n} score_i \tag{1}$$

where n = 9.

We used the sums to calculate the mean score, m_i, of each factor, i. We then undertook an analysis of variance (ANOVA) at the 95 % confidence level to compare each company's response with the others and the overall dataset, similarly to other studies that compared factors from an empirical data set (e.g. Mahadevan et al., 2023). We also determined the relative differences in scores from the mean of each supply chain actor, in other words, we determined the one-dimension Euclidean distance, which is a simple formulation used to measure the similarity/dissimilarity between two data sets (Zakeri et al., 2024),

$$d_i(m_i, score_i) = m_i - score_i \tag{2}$$

Thus, we systemically determined where the case companies had similar/dissimilar perspectives regarding the importance of each critical success factors where there are large dissimilarities we assess them as potential tensions and misalignment that may exist in the supply chain. A similar approach has been adopted in other research on supply chain tension (e.g. Rosca et al., 2019) although ours is the first with respect to critical success factors related to remanufacturing.

We then performed an inductive study by comparing the workshop responses with the existing literature. More specifically, we compared our findings with those of Ziout et al. (2014), who provided a holistic and systematic method to determine circular economy decisions that was tested with an automotive sector case, as well as referring the other literature listed in Table 1.

4. Findings

4.1. Remanufacturing business drivers and barriers

The main drivers identified in the existing studies related to the remanufacturing and reuse of ship equipment were cost savings, shorter lead times for equipment and vessel construction, and an increased volume of vessel conversions due to stricter environmental regulations and advancements in technology (Daniel and Lee, 2022; Okumus et al., 2023a). Our study partly supports previous findings suggesting that sourcing used equipment is often cheaper than buying new equipment, but remanufacturing and reusing does not always guarantee cost savings. In fact, low remanufacturing cost was regarded as a driver only by suppliers B and C. Supplier B stated that *"remanufacturing **cranes** by reusing the existing steel structure offers both cost savings and a more affordable solution for the end customer compared to building new cranes"*. A more important driver for remanufacturing seems to be the opportunity to offer short delivery times (A, D, F). Yard F stated that *"to refurbish used equipment can be as expensive as new equipment, but the delivery time is shorter"*. Stricter environmental regulations are increasingly becoming a motivating driver for remanufacturing (C, E, I). Yard E stated that *"the main trigger for circularity is the regulations from EU"*. An additional driver in shipbuilding is the ability to extend the lifespan of vessels through remanufacturing or upgrading equipment (A, C, D, E, F, G, H). Supplier C stated that *"the average lifespan of an **offshore ship** is 15-20 years. Upgrading these ships has the potential to extend their operational life to 30 years."*

A study by Okumus et al. (2023a) indicates that remanufacturing and reuse are worthwhile only for equipment in the ship's machine room. Our study indicates that remanufacturing and reuse also has potential for other types of equipment on board. The following equipment was identified by the workshop participants:

- **Main engines** (A, C, D, F, H)
- **Cranes and winches** (B, D, E, F, G)
- **Cylinders and hydraulic pumps** (C, D, G)
- **Generator sets** (C, F, H)
- **Propulsion systems and thrusters, gear houses** (F, H)
- **Compressors** (A)
- **Propellors** (C)
- **Electro engines** (H)

The listed equipment are mechanical products that are easy to access on board a ship and where replacing the equipment or components is easy. Our study also found that **electrical equipment** was regarded as more difficult to remanufacture/reuse because of its short life cycles and therefore its reduced restorative potential (C, D, F, G, H). The exception was **electro engines**, which have a long technical life and can be a candidate for remanufacturing/reuse.

Multiple barriers to remanufacturing/reusing equipment in shipbuilding might explain the low and varying prevalence of the activity as a business domain. Existing studies have identified regulations, costs, lack of competencies, demand, and reverse supply infrastructures as the main barriers (Milios et al., 2019; Okumus et al., 2023a). Our study confirms this, except for the lack of competencies, which is not reflected in our results (Table 3).

4.2. Critical factors for remanufacturing decisions in the Norwegian shipbuilding industry

This section presents the critical factors influencing decision making about remanufacturing or reuse of ETO ship equipment that resulted from the workshops and follow-up interviews. The factors are listed in descending order in Table 4 based on the ranking given by the respondents. The individual rankings from each company are listed in Appendix B.

Table 3
Barriers to remanufacturing/reusing equipment in the shipbuilding industry.

Barriers	Cases and quotes
High manufacturing cost	A, D, F, H, and I Supplier D: *"A major barrier is the remanufacturing costs; it is more expensive to remanufacture than to make a new* ***cylinder.****"*
Regulations	A, E, F, and H Yard F: *"The current regulations are a bit outdated because they require original certification documents in order to get the class certification renewed." (****Main engines, Cranes and winches, Generator sets, Propulsion systems and thrusters, Gear houses****)* Owner *H: "Our contracts only have requirements about emissions from maritime transport, there are not yet any requirements about emissions from the purchase of the vessel". (Main engines, Generator sets, Propulsion systems and thrusters, Gear houses, Electro engines)* *Yard E: "A major challenge for upgrading/retrofit is the regulations".* ***(Cranes and winches)***
Limited/varying demand for used ship equipment	A, B, D, and I Supplier D: *"We are an ETO supplier with a high level of customisation. Product design is customised, and demand for used models and parts varies from year to year".* ***(Main engines, Cranes and winches, Cylinders and hydraulic pumps)*** Supplier B: "*We don't get requests for remanufacturing services every year".* ***(Cranes and winches)***
Supply and the lack of a reverse supply chain infrastructure	E and H *Yard E: "If we should do more remanufacturing, limited access to used equipment is a large barrier".* ***(Cranes and winches)*** *Owner H: "The purchase of more used equipment requires an ecosystem of suppliers for used equipment".* ***(Main engines, Generator sets, Propulsion systems and thrusters, Gear houses, Electro engines)***

The workshop participants responded that the list in Table 4 covered most of the critical factors that need to be considered. Their feedback also indicated three additional factors that should be included: 1) delivery/replacement time, i.e. the time to deliver and replace a product on board (A, F, H), 2) available supply in the market, i.e. the number of products available in the used equipment market (H), and 3) greenhouse gas emissions, i.e. the amount of greenhouse gas emissions the product is producing (E, F).

4.3. Insights from analysing factors across supply chain actors in the shipbuilding industry

We also analysed the potential tensions and areas of agreement between supply chain actors for each of the category of identified factors (e.g. product design, product condition, supply chain, industry). The ANOVA analysis at the 95 % confidence level of all the companies' responses shown in Appendix B is given in Fig. 2. We also undertook a similar ANOVA analysis to include the mean and then a pair-wise comparison between each company's response with the overall mean. Statistically, there is no evidence to suggest that there were any dissimilarities between responses.

However, we were also interested in a deep dive into individual factors and thus undertook a Euclidian-distance analysis as described in Section 3.3. The factors and their deviation from the mean are listed in Appendix C, and where tensions exist, defined as deviations greater than ± 1.3 from the mean, they are depicted in Fig. 3.

The results show that damage (D 1.3, E 1.7, G 1.7, H 1.3, I 1.3) is a factor with the potential for tensions across different cases. This factor elicited the most frequent results in our analysis of tensions and agreements. Organisations E and G (newbuild yard and owner) considered

Table 4
Critical factors influencing remanufacturing and reuse options in ETO shipbuilding.

Critical Factors	Description	Sum
Product documentation	Certificates, CAD drawings, maintenance reports, operational vessel data	40
Quality	Degree to which the product meets requirements and standards	37
Manufacturing costs	Cost of manufacturing a new product vs. remanufacturing a used product	36
Fuel efficiency	Fuel efficiency of a new product vs. a used product	36
Fatigue/wear	Extent of material fatigue and wear from operations	35
Operations costs	The cost of operating a new product vs. operating a used product	35
Regulations	Regulations that govern maritime operations (classification, public regulations and policies, etc.)	35
Interchangeable components	Standardised components that can be reused in a range of products	34
Design for disassembly	Design for disassembly and reuse/remanufacturing	34
Damage	Physical damage and extent of rust, corrosion, or other forms of deterioration	33
Technical lifetime	The time a product can technically perform/function before it must be replaced	33
Functional compatibility	Fit between required and actual performance/features of the used product	31
Interoperability	Technical standards and interfaces for easy product transfer and installation in a range of vessels	31
Technical complexity	The intricacy and interdependence of various components of the product	31
Product value	Top of the line products vs. basic simpler products	31
Product type	Type of product (mechanical, hydraulic, electric, or software)	30
Effective reverse supply chain	The series of activities required to retrieve a used product (collection) and to refurbish or remanufacture it (operations)	29
Material value	Value of the materials used in products	28
Technology obsolescence	The risk that a new version of a particular technology makes the used product obsolete	28
Material composition	Type of materials used in a product (including hazardous or polluting substances)	25
Collection transport distance	Distance from the product location to a facility for restorative operations	24
Accessibility and retrievability	Accessibility and retrievability of products from ships	23

this a less important factor (relative to the average score), while D, H, and I considered this factor more important (supplier, owner, and classification society). An additional area that showed differences in the perceived level of importance was collection transport distance (A 1.3, B 1.7, E 1.3, G 1.3). The results indicate a high importance ranking relative to the average for case A, E, and G (supplier, newbuild yard, and owner), but there is an interesting tension between different suppliers (A and B) where supplier B considered this not to be so important.

The analysis shows that three factors had perceived tensions between two cases, including product type, product value and material composition. The analysis of the ranking of product type reveals a tension between supplier B and owner/operator G (B 1.7, G 1.3), where B considered this very important, but G less important. Product value was a further factor with tensions (A 2.4, G 1.6), where supplier A and owner/operator G perceived a different level of importance. Supplier A considered this less important, whereas owner/operator G considered it more important (E 1.8, H 2.2). Analysis of rankings for material composition revealed a tension between newbuild yard E and owner/operator H.

There were also areas where companies agreed. Suppliers A and D both considered regulation to be much less of an issue than the average ranking (A 1.9, D 1.9). There was also an agreement between supplier B and newbuild yard E in ranking material value as a more important

SUMMARY

Groups	Count	Sum	Average	Variance
A	22	70	3.181818182	1.774891775
B	22	79	3.590909091	1.396103896
C	22	80	3.636363636	1.385281385
D	22	73	3.318181818	1.37012987
E	22	77	3.5	1.214285714
F	22	78	3.545454545	1.021645022
G	22	82	3.727272727	0.779220779
H	22	86	3.909090909	1.134199134
I	22	74	3.363636364	0.528138528

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	8.636363636	8	1.079545455	0.91625842	0.504133454	1.987658546
Within Groups	222.6818182	189	1.178210678			
Total	231.3181818	197				

Fig. 2. Output of the ANOVA analysis of the dataset.

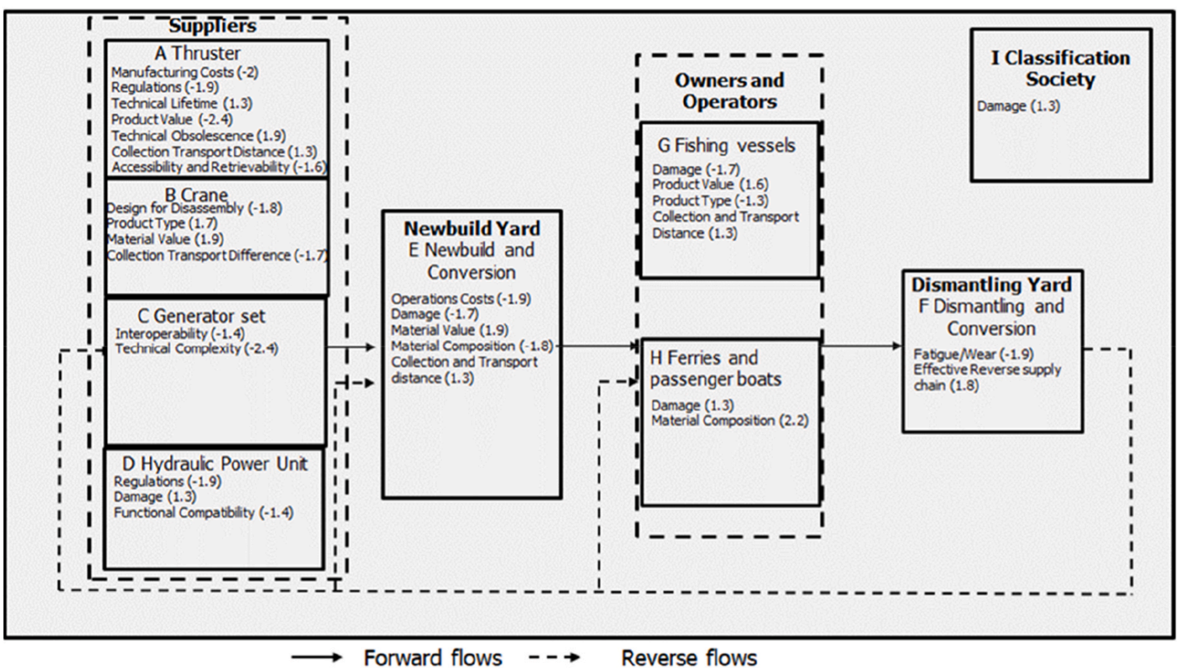

Fig. 3. Tensions in the studied closed-loop supply chain.

factor than the average ranking would suggest (B 1.9, E 1.9). All other factors only appeared once in our analysis, and thus there were no apparent tensions with other companies.

5. Reflection on critical success factors for remanufacturing and reuse of ETO equipment in shipbuilding

This section reflects on ETO ship equipment and critical success factors for remanufacturing and reuse based on the study's inductive findings and the literature. First, factors impacting remanufacturing and reuse in the shipbuilding industry are compared and discussed in relation to critical factors from generic circular research on remanufacturing and reuse. Second, tensions in the supply chain impacting remanufacturing and reuse are discussed.

5.1. *Factors impacting remanufacturing and reuse*

In Table 5, the critical factors developed by Ziout et al. (2014) from the literature are compared to the factors identified in this paper's inductive and empirical study. Ziout et al. (2014) developed categories and factors aligned with the PESTEL analysis and covered all macro forces that a company is facing in product recovery. The main categories adopted in our comparison are 'engineering', 'business', and 'environment'. 'Society' was not included because no societal factors were identified. Factors that might be subject to tension across the supply chain from section 4.3 are marked with (*) and are discussed in section 5.2.

Our study identifies many of the same factors as Ziout et al.'s (2014) generic study of critical factors for remanufacturing related to

Table 5
Comparison of decision-making factors in the shipbuilding study and the generic circular study by Ziout et al. (2014).

Categories	Shipbuilding Critical Factors	Criticality	Critical factors (Ziout et al., 2014)	Comparison of critical factors
Product	Product documentation	40	***Not identified***	***New***
	Quality	37	***Not identified***	***New***
	Fatigue/wear	35	Wear out life	Direct fit
	Interchangeable components	34	Standard or interchangeable item	Very much related
	Design for disassembly	34	Disassembly effort	Very much related
	*Damage	33	***Not identified***	***New***
	Technical lifetime	33	Item useful lifetime	Direct fit
	Interoperability	31	Standard or interchangeable item	Very much related
	Functional compatibility	31	***Not identified***	***New***
	Technical complexity	31	Product architecture, level of integration	Direct fit
	*Product type	30	***Not identified***	***New***
	Technology obsolescence	28	Technology/design cycle	Direct fit
	*Material composition	25	Materials separability	Direct fit
Process	Accessibility and retrievability	23	Collection costs	Very much related
Engineering		**445**		
Market	Manufacturing costs	36	***Not identified***	***New***
	Operations costs	35	***Not identified***	***New***
	*Product value	31	New item value	Very much related
	Material value	28	Used item value	Very much related
Supply-demand	Effective reverse supply chain	29	Collection cost + Recovery process cost	Very much related
	*Collection transport distance	24	EOL product location	Direct fit
	Delivery/replacement time	–	***Not identified***	***New***
	Supply availability	–	***Not identified***	***New***
Legal and political	Regulations	35	***Not identified***	***New***
Business		**218**		
	Fuel efficiency	36	Air emissions	Very much related
	Greenhouse gas emissions	–	Air emissions	Very much related
Environment		**36**		

'engineering' (such as fatigue/wear, technical lifetime, and interchangeable components), 'business' (such as new product value, material value, and collection transport distance) and 'environment' (such as fuel efficiency, and greenhouse gas emissions). A range of new critical factors are identified that at least to some extent can be related to the specific characteristics of the shipbuilding industry, and that are important for managers to be aware of when making remanufacturing decisions.

Most of the factors in our study are related to the main category 'engineering', particularly specifications and conditions of the product (thruster, crane, generator set, hydraulic power unit), but some are also related to the process of core retrieval and installation of the remanufactured/refurbished product in vessels. Factors related to the 'business' category are market factors, such as the cost of a new product compared to a recovered product, supply-demand factors, such as collection transport distance and an effective reverse supply chain, and legal and regulatory factors. Only two factors in our study are related to the 'environment' category. These are fuel efficiency and greenhouse emissions, which are considered essential in creating a green shift in the shipbuilding industry. None of the factors are related to 'society'.

Ziout et al. (2014) developed factors based on the literature and did not rank them as in our study. In contrast to our study, they tested the factors through a single case study of an OEM in the automotive industry. By comparing our study to this automotive study, we recognise that both empirical studies reveal a lack of prioritisation of environmental and social factors. The distribution of preferences in the automotive study by Ziout et al. (2014) were 0.460 for engineering factors, 0.308 for business factors, 0.170 for environmental factors, and only 0.062 for societal factors. In comparison, the distribution of weighting in our study was 0.637 for engineering factors, 0.312 for business factors, 0.052 for environmental factors, and 0.0 for societal factors.

The focus on 'engineering' is due to ships being capital-intensive, large, and durable products designed to have a relatively long lifespan operating in harsh conditions. Because ships are regulated through global classification societies they therefore need to be designed to satisfy regulations and be certified regularly regarding quality and performance. These certification checks require that the equipment onboard needs to be well documented and registered, and this needs to include original equipment and as well remanufactured products.

The 'business' category is ranked second in our study due to the degree of customisation of ships in the Norwegian sector. Such ETO products are built as 'one-of-a-kind' variants and in low volumes to satisfy the functional requirements given by a particular client/ship owner that is competing in a global shipping market. Used equipment, such as main engines, cranes, winches, propulsion systems, thrusters, gear houses and compressors that fit a certain ship are therefore not commodities, and it might be challenging to find a market to sell and a market to buy a specific piece of equipment with satisfactory functionality, dimensions, quality, and performance.

The 'environmental' category is ranked low, and the 'society' category received no attention in the emprical evidence, indicating low 'environmental' awareness and/or motivation by the companies, and suggesting little impact from 'society', whether in the form of slowly emerging governmental legislation or social pressure groups.

Given the foregoing, and in the spirit of self-reflective engineering management practice (Ford et al., 2024), we propose the following questions for those seeking to make remanufacturing and reuse decisions across the supply chain:

Engineering:

- Product documentation and quality: How do we ensure the equipment has sufficient documentation to meet the technical standards that are required for class certification?
- Damage: What are the implications of any physical damage or form of deterioration, like rust, on the equipment?
- Functional compatibility: Given that these are customized, low volume products, how do we maintain sufficient fit between the functionality/performance of the equipment and customer requirements?
- Product type: What kinds of equipment are most suited for remanufacturing, given that mechanical and hydraulic equipment is mostly easily remanufactured, while electrical and software are more challenging to reuse?

Business:

- Manufacturing and operating costs: What is the cost of remanufacturing ship equipment versus producing new, and what are their relative in-service operating costs?
- Delivery/replacement time and supply availability: How is a sufficient supply in terms of specified volume, quality, and delivery time satisfied?
- Regulations: How can the remanufactured equipment comply with the classification standards issued and checked by the ship class societies to be certified for the specified fitness of a ship for a particular use or service?

Environment (and Society):

- Emissions: How can one evaluate the investment costs in new versus used solutions with due consideration of fuel efficiency and changing regulations related to emissions?

5.2. Tensions impacting remanufacturing and reuse

The analysis presented in Section 4.3 highlights that there are likely to be areas of tension, but also agreement, across the factors for remanufacturing. Across the different types of organisations included in our analysis (i.e. suppliers, owners and operators, newbuild yard, dismantling yard, and classification societies), there are understandable differences in terms of priority and 'worldviews'. Our analysis shows tensions between suppliers and the owner/operators on issues relating to the suitability of product types and product value. Hence, it is apparent from our research that disparities exist between upstream and downstream actors with respect to product type and product value. There were also areas of tension between newbuild yard and owner/operators relating to material composition. The success factors of collection transport and damage also elicited varying perceptions of importance across the types of organisations and their position in the supply chain.

It is also possible that there may exist different priorities among certain organisational groups. For example, different suppliers (A and B) revealed tensions between perceptions of the importance of transport distance. This may be due to the relative ease with which the product types may be transported at EOL or to differences in business model. Supplier A has their production facilities in Norway, while supplier B has outsourced production. Their technicians mainly undertake remanufacturing and refurbishment on board, and thus distance is not a critical factor. Supplier B stated that "*when a crane is transferred from one vessel to another, we step in as an engineering partner, carrying out the necessary adjustments and conversations to ensure the crane can serve the same purpose on board the new vessel*".

There was also evidence that the group of supplier cases (A, B, C, and D) had a different level of strategic importance and capability in remanufacturing and aftermarket supply. Supplier D stated that *"we do remanufacturing and refurbishment as a service, but have not established a reverse supply chain to collect and remanufacture products for sale or to be included in cylinder exchange systems for customers"*. Only supplier (C) has a 'buy back' supply chain, whereas the other three suppliers, A, B and D, undertake aftermarket and overhaul on a contract basis only, and thus, it is not a core business process. These differences underline the importance of collective orchestration, which has been highlighted in previous literature (e.g. Oskam et al., 2021; Tschiedel et al., 2024). Interestingly, suppliers A and D did not rank the factor regulations highly in terms of importance. Supplier D stated that *"class certification requirements significantly increase costs for ship owners"*. However, they provide *"more jobs for the supplier"*. This challenges previous work that has suggested that regulations is a key driver of circular economy (Singhal et al., 2020; Okumus et al., 2023a), but also opens questions for future research in terms of the role of regulation to incentivise more circular processes and behaviours across the supply chain.

Our results confirm the potential for interfirm tensions as previously identified by Manzhynski and Figge (2020), although what the trade-off requirements are is still not evident. Nevertheless, power relationships in such an ETO supply chain often reside with upstream players (Centobelli et al., 2023), where there is often a design innovation 'push' leading to 'customer' adoption. The lack of innovation push by suppliers may be due to the relative infancy of circular economy principles within the specific shipbuilding supply chain. This suggests an opportunity for deriving either of the two models for creating a circular economy business model suggested by Oskam et al. (2021). Because the research findings suggest that the downstream 'customers' have established their boundary conditions for embracing circular economy principles (as per Schultz, 2022) they can establish mutual trust models and can collectively orchestrate a viable sustainable business model with those upstream actors that closely align with them. Where tensions are too high, the collaborative players can collectively search for new actors and bring them into the fold.

Building on the idea of collective orchestration, ETO shipbuilding supply chains consist of multiple organisations engaged in performing complex engineering tasks, and thus, co-ordination of interrelated decisions is a critical issue. An important task, therefore, is to seek consensus, or 'accommodation' (Mello et al., 2017), between different worldviews and organisations in relation to key decisions over the product lifecycle. Our research indicates that areas of tension that will need to be openly debated via reflective questioning (Ford et al., 2024) are:

- Why is remanufacturing and reuse strategically important to each actor as well as the whole supply chain?
- How will regulation impact remanufacturing operations?
- Who has the capability, motivation and incentive to remanufacture and reuse?
- What will be the cost of transport, and who will bear the cost?

6. Conclusion

Our inductive study has identified several factors that Norwegian ETO shipbuilding actors consider to be of relevance when making decisions regarding remanufacturing and reuse of equipment (Research Question 1). The top four critical success factors are: product documentation, quality, manufacturing costs, and fuel efficiency (Research Question 2). When compared to the existing literature on factors to consider we find some alignment but also 10 new ones, such as the inclusion of product documentation, quality and damage (Research Question 3). Our results indicate that the environmental awareness in our sample of companies from the Norwegian shipbuilding industry still can be strengthened, especially the continued enforcement of the European Union's CSRD, and that their focus is mainly on technology and business. The strong emphasis on the engineering dimension can be explained by the characteristics of ETO products, which are capital intensive and technologically complex. While our case companies are all in the ETO shipbuilding sector, we cannot at this stage draw conclusions on potential differences with non-ETO shipbuilding organisations.

Our study also explored the tensions between the actors in terms of factor importance (Research Question 4). This has implications for ensuring system-wide adoption of circularity in the shipbuilding supply chain.

Experiences from previous studies on closed-loop supply chains suggest that when existing actors in the forward supply chain do not perceive a benefit in participating in the reverse supply chain, there is an opportunity for third parties to emergence, such as dedicated remanufacturers and reverse logistics providers.

We are yet to identify such players in the Norwegian ETO shipbuilding sector, which is an avenue for further research with a more in-depth consideration of the various forms of tensions that may exist.

We have also raised several self-reflective questions that need to be addressed by the sector. These may be answered in several ways:

1. As part of the next policy document for research in the Norwegian maritime sector.
2. Through the establishment of a digital platform for trade in the industry, either by the industry itself or with support from the government.
3. Inclusion in existing green transformation programmes in the industry, e.g. the Norwegian Blue Maritime Initiative.
4. By companies themselves as part of their own project management processes when delivering their products and associated services.

This study raises some interesting avenues for future research. In particular, there is a need for further research on who should take the lead in facilitating the collective orchestration of tensions and conflicts in priorities. The findings also indicate varying levels of strategic commitment and capability for remanufacturing across organisational types, so further research could seek to investigate approaches to improve remanufacturing capability across the supply chain. Finally, further research could seek to develop comparisons of ETO types in circular supply chains to facilitate learning and best practices. This may be facilitated by the development of further case studies specifically for the shipbuilding sector as currently we have identified an extremely limited number of existing case studies in the authoritative academic literature.

CRediT authorship contribution statement

Erlend Alfnes: Writing – review & editing, Writing – original draft. **Jonathan Gosling:** Writing – review & editing, Writing – original draft. **Mohamed Naim:** Writing – review & editing, Writing – original draft. **Heidi C. Dreyer:** Writing – review & editing, Writing – original draft. **Hedda Constance Høgseth:** Writing – original draft, Investigation, Conceptualization.

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Declarations of competing interest

none.

Appendix A. Interview guide and relevant information:

When reading the relevant information below, please keep the questions below in the back of your mind to reflect upon your company's operations.

Introduction

1. Thank them for participating and ask if the interview can be recorded
2. Ask whether it is possible to disclose their name and professional information in the article
3. Ask the interview participants about their professional experience
4. Ask whether the participant can find time to read and confirm the interview content after it is transcribed

1. Information about the company
   - Which type of products do you see as fit for implementing circular activities?
   - Annual volume of the company (quantity per year)?
     o 1-10
     o 11-100
     o 101-1000
     o 1001-10,000
     o 10 000
   - Duration (weeks per project)?
     o 1-10
     o 11-50
     o 51-100
     o 100
   - Cost per unit? (Thousand Euros)
     o 1-10
     o 11-100
     o 101-1000
     o 1001-10,000
     o 10 000
   - Engineering hours (hours per project)?
     o 0-100
     o 101-1000
     o 1001-10,000
     o 10 000

2 Questions about the supply chain
   - To what degree does the company operate with circular economy activities?
     o Reuse
     o Repair
     o Refurbishment/Remanufacturing
     o Reuse
   - What have been the barriers/challenges when adapting the operations to circular economy activities?

  - o If not, what has been stopping the company from initializing this?
  - o e.g., Industry standards, economic reasons, low customer demand
- What changes must be made to the current operations to ease the implementation of circular economy activities?
- Which circular economy activities are the company most likely to adapt to?
  - o Reuse
  - o Repair
  - o Remanufacturing and refurbishment
  - o Recycling
- What circular activities have the largest potential to give economic benefits to the company?

3 Remanufacturing/refurbishment
- What does remanufacturing/refurbishment mean for the company?
- How is remanufacturing/refurbishment integrated into your engineer-to-order supply chain?
- Which type of products have the greatest potential for remanufacturing/refurbishment?
- Which factors determine the potential for remanufacturing/refurbishment? Examples?

Appendix B. Ranking of factors

Critical Factors	Description	Cases									Sum
		A	B	C	D	E	F	G	H	I	
Product documentation	Certificates, CAD drawings, maintenance reports, operational vessel data	4	4	4	5	5	5	4	5	4	40
Quality	Degree to which the product meets requirements and standards	4	3	5	4	3	5	5	5	3	37
Manufacturing costs	Cost of manufacturing a new product vs. remanufacturing a used product	2	5	5	5	4	3	5	4	3	36
Fuel efficiency	Fuel efficiency of a new product vs. a used product	5	4	3	3	5	3	4	5	4	36
Fatigue/wear	Extent of material fatigue and wear from operations	3	5	5	3	3	2	4	5	5	35
Operations costs	The cost of operating a new product vs. operating a used product	5	5	3	4	2	3	5	5	3	35
Regulations	Regulations that govern maritime operations (classification, public regulations and policies, etc.)	2	5	5	2	3	5	4	5	4	35
Interchangeable components	Standardised components that can be reused in a range of products	3	3	5	4	4	5	4	3	3	34
Design for disassembly	Design for disassembly and reuse/remanufacturing	4	2	5	5	5	3	4	3	3	34
Damage	Physical damage and extent of rust, corrosion, or other forms of deterioration	3	4	4	5	2	3	2	5	5	33
Technical lifetime	The time a product can technically perform/function before it must be replaced	5	3	4	4	4	3	3	4	3	33
Functional compatibility	Fit between required and actual performance/features of the used product	3	4	4	2	4	3	4	3	4	31
Interoperability	Technical standards and interfaces for easy product transfer and installation in a range of vessels	4	4	2	4	3	4	3	4	3	31
Technical complexity	The intricacy and interdependence of various components of the product	4	4	1	3	4	4	4	4	3	31
Product value	Top of the line products vs. basic simpler products	1	3	4	3	4	4	5	4	3	31
Product type	Type of product (mechanical, hydraulic, electric, or software)	3	5	3	3	3	4	2	3	4	30
Effective reverse supply chain	The series of activities required to retrieve a used product (collection), and to refurbish or remanufacture it (operations).	2	3	4	1	4	5	3	4	3	29
Material value	Value of materials used in products	2	5	3	2	5	4	3	2	2	28
Technology obsolescence	The risk that a new version of a particular technology makes the used product obsolete	5	3	2	3	2	3	3	4	3	28
Material composition	Type of materials used in product (including hazardous or polluting substances)	1	2	4	2	1	3	4	5	3	25
Collection transport distance	Distance from product location to facility for restorative operations	4	1	2	2	4	2	4	2	3	24
Accessibility and retrievability	Accessibility and retrievability of products from ships	1	2	3	4	3	2	3	2	3	23

Appendix C. Relative importance analysis between supply chain actors

Critical Factors	Description	Sum	Mean	A	B	C	D	E	F	G	H	I
Product documentation	Certificates, CAD drawings, maintenance reports, operational vessel data	40	4.4	−0.4	−0.4	−0.4	0.6	0.6	0.6	−0.4	0.6	−0.4
Quality	Degree to which the product meets requirements and standards	37	4.1	−0.1	−1.1	0.9	−0.1	−1.1	0.9	0.9	0.9	−1.1
Manufacturing costs	Cost of manufacturing a new product vs. remanufacturing a used product	36	4.0	**−2.0**	1.0	1.0	1.0	0.0	−1.0	1.0	0.0	−1.0
Fuel efficiency	Fuel efficiency of a new product vs. a used product	36	4.0	1.0	0.0	−1.0	−1.0	1.0	−1.0	0.0	10	0.0
Fatigue/wear	Extent of material fatigue and wear from operations	35	3.9	−0.9	1.1	1.1	−0.9	−0.9	**−1.9**	0.1	1.1	1.1
Operations costs	The cost of operating a new product vs. operating a used product	35	3.9	1.1	1.1	−0.9	0.1	−1.9	−0.9	1.1	1.1	−0.9
Regulations	Regulations that govern maritime operations (classification, public regulations and policies, etc.)	35	3.9	**−1.9**	1.1	1.1	**−1.9**	−0.9	1.1	0.1	1.1	0.1
Interchangeable components	Standardised components that can be reused in a range of products	34	3.8	−0.8	−0.8	1.2	0.2	0.2	1.2	0.2	−0.8	−0.8
Design for disassembly	Design for disassembly and reuse/remanufacturing	34	3.8	0.2	−1.8	1.2	1.2	1.2	−0.8	0.2	−0.8	−0.8
Damage	Physical damage and extent of rust, corrosion, or other forms of deterioration	33	3.7	−0.7	0.3	0.3	1.3	**−1.7**	−0.7	**−1.7**	1.3	1.3

(*continued on next page*)

(*continued*)

Critical Factors	Description	Sum	Mean	A	B	C	D	E	F	G	H	I
Technical lifetime	The time a product can technically perform/function before it must be replaced	33	3.7	1.3	−0.7	0.3	0.3	0.3	−0.7	−0.7	0.3	−0.7
Functional compatibility	Fit between required and actual performance/ features of the used product	31	3.4	−0.4	0.6	0.6	−1.4	0.6	−0.4	0.6	−0.4	0.6
Interoperability	Technical standards and interfaces for easy product transfer and installation in a range of vessels	31	3.4	0.6	0.6	−1.4	0.6	−0.4	0.6	−0.4	0.6	−0.4
Technical complexity	The intricacy and interdependence of various components of the product	31	3.4	0.6	0.6	**−2.4**	−0.4	0.6	0.6	0.6	0.6	−0.4
Product value	Top of the line products vs. basic simpler products	31	3.4	**−2.4**	−0.4	0.6	−0.4	0.6	0.6	1.6	0.6	−0.4
Product type	Type of product (mechanical, hydraulic, electric, or software)	30	3.3	−0.3	1.7	−0.3	−0.3	−0.3	0.7	−1.3	−0.3	0.7
Effective reverse supply chain	The series of activities required to retrieve a used product (collection), and to refurbish or remanufacture it (operations).	29	3.2	−1.2	−0.2	0.8	**−2.2**	0.8	**1.8**	−0.2	0.8	−0.2
Material value	Value of materials used in products	28	3.1	−1,1	**1.9**	−0.1	−1.1	**1.9**	0.9	−0.1	−1.1	−1.1
Technology obsolescence	The risk that a new version of a particular technology makes the used product obsolete	28	3.1	**1.9**	−0.1	−1.1	−0.1	−1.1	−0.1	−0.1	0.9	−0.1
Material composition	Type of materials used in product (including hazardous or polluting substances)	25	2.8	−1.8	−0.8	1.2	−0.8	**−1.8**	0.2	1.2	**2.2**	0.2
Collection transport distance	Distance from product location to facility for restorative operations	24	2.7	1.3	−1.7	−0.7	−0.7	1.3	−0.7	1.3	−0.7	0.3
Accessibility and retrievability	Accessibility and retrievability of products from ships	23	2.6	−1.6	−0.6	0.4	1.4	0.4	−0.6	0.4	−0.6	0.4

Data availability

The data that has been used is confidential.

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