Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

Hedda Constance Høgseth

Enhancing Remanufacturing Potential and Mitigating Uncertainties through Digital Technologies

A multiple case study researching stakeholders of Norwegian maritime industry.

Master's thesis in Engineering and ICT
Supervisor: Erlend Alfnes
Co-supervisor: Gabriele Hofinger Jünge, Nina Pereira Kvadsheim
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NTNU
Kunnskap for en bedre verden

Abstract

This master's thesis examines the potential for transitioning engineer-to-order supply chains in the maritime industry towards a circular economy and investigates the role of digital technology in supporting the integration of remanufacturing practices. The study aims to understand the factors that determine the potential for remanufacturing used products and the uncertainties associated with implementing remanufacturing in the supply chain. Additionally, it explores how digital technologies can address these uncertainties and facilitate the effective implementation of remanufacturing. The research methodology includes a literature study for theoretical background and a multiple case study analysis involving semi-structured interviews and a questionnaire.

The study identifies 16 key factors that influence the potential for remanufacturing at the product level, contributing a comprehensive list of factors specific to the maritime industry. It also highlights the uncertainties that arise when integrating remanufacturing into engineer-to-order supply chains, encompassing supply, process, demand, and control uncertainties. Moreover, the research emphasizes the role of digital technologies, such as data analytics, Internet of Things , simulation and modeling, and cloud technology, in addressing these uncertainties and supporting remanufacturing implementation.

The findings of this study have practical implications for engineer-to-order companies considering the adoption of remanufacturing practices. The identified factors can assist in assessing the potential for remanufacturing at the product level, while the insights into supply chain uncertainties can help companies navigate challenges during integration. The suggested use of digital technologies provides guidance on how companies can leverage these tools to enhance remanufacturing operations.

However, it is important to acknowledge the limitations of the study, including variations in expertise among the case companies and an uneven distribution of stakeholders. Future research should focus on understanding stakeholder-specific uncertainties and conduct case studies on individual stakeholders in the maritime industry. Additionally, exploring the economic benefits of remanufacturing and addressing existing regulatory barriers are important areas for further investigation.

By shedding light on the factors influencing remanufacturing, supply chain uncertainties, and the role of digital technologies, this thesis contributes to the knowledge base on sustainable practices in the maritime industry. It is anticipated that the insights gained

from this study will encourage companies to embrace remanufacturing as a pathway to sustainability and economic prosperity in the sector. Ultimately, this research supports the advancement of production management strategies in the maritime industry towards a more sustainable and resource-efficient future, and a step closer to the final goal which is the circular economy.

Sammendrag

Denne masteroppgaven utforsker potensialet for å implementere en sirkulær økonomi i engineer-to-order verdikjeder i den maritime industrien, og undersøker rollen digital teknologi spiller i integreringen av reproduksjon. Målet med studien er å undersøke hvilke faktorer som påvirker muligheten for å reprodusere brukte produkter, samt usikkerheter knyttet til implementeringen av slike aktiviteter i verdikjeden. Videre utforsker oppgaven hvordan digitale teknologier kan håndtere disse usikkerhetene og bidra til effektiv implementering av reproduksjon. Forskningsmetodene inkluderer en litteraturstudie for å skaffe teoretisk bakgrunn, samt casestudier av flere bedrifter ved hjelp av semi-strukturerte intervjuer og spørreskjema.

Studien identifiserer 16 nøkkelfaktorer som påvirker potensialet for reproduksjon på produktnivå, og presenterer en omfattende liste over faktorer som er spesifikke for den maritime industrien. Oppgaven fremhever også usikkerheter som oppstår ved integreringen av reproduksjon i engineer-to-order verdikjeder, inkludert forsynings-, prosess-, etterspørsels- og kontrollusikkerheter. Videre understreker oppgaven rollen til digitale teknologier som blant annet dataanalyse, tingenes internett, simulering og modellering, samt skyteknologi, for å takle disse usikkerhetene og støtte implementeringen av reproduksjon i slike verdikjeder.

Resultatene fra denne studien har praktiske implikasjoner for engineer-to-order selskaper som vurderer å innføre reproduksjon i verdikjeden sin. De identifiserte faktorene kan hjelpe med å vurdere muligheten for reproduksjon på produktnivå, mens innsikten i usikkerhetene som kan oppstå i verdikjeden kan hjelpe bedrifter med å takle utfordringene ved integrasjon. Den foreslåtte bruken av digitale teknologier gir veiledning om hvordan bedrifter kan utnytte slike teknologier for å lette integrasjonen av reproduksjon.

Det er imidlertid viktig å erkjenne begrensningene ved denne studien, inkludert variasjoner i kompetansenivå blant casebedriftene og en ujevn fordeling av interessenter. Fremtidig forskning bør fokusere på å forstå interessentspesifikke usikkerheter og gjennomføre casestudier på individuelle interessenter i den maritime næringen. Videre er det viktige områder som bør undersøkes nærmere, som de økonomiske fordelene ved reproduksjon og håndtering av eksisterende regulatoriske barrierer.

Ved å belyse faktorene som påvirker reproduksjon, usikkerhet i verdikjeden og rollen til digitale teknologier, bidrar denne oppgaven til kunnskapsgrunnlaget for bærekraftige praksiser i den maritime industrien. Forventningen er at innsiktene fra denne studien vil oppmuntre selskaper til å omfavne reproduksjon som en vei mot bærekraft. Til slutt støtter denne oppgaven fremdriften av produksjonsstrategier i den maritime industrien mot en mer bærekraftig og ressurseffektiv fremtid, og bringer oss nærmere det endelige målet om en sirkulær økonomi.

Preface

This paper is the result of the course TPK4930 - Production Management, Master's Thesis at the Norwegian University of Science and Technology (NTNU). The thesis is written by Hedda Constance Høgseth during the spring of 2023, as the final part of the 5-year master's degree program Engineering and ICT under the Department of Mechanical and Industrial Engineering, with focus on Operational Management.

The thesis is a continuation of a specialization project written during the fall of 2022, which examined how Industry 4.0 technologies could aid engineer-to-order companies to transition towards the circular supply chain, entitled "Utilizing Industry 4.0 technology to aid ETO companies in transitioning to a circular supply chain".

The process of conducting this master's thesis has provided me with valuable experience not only in scientific research but a great learning experience personally. I would like to thank my supervisor, Professor Erlend Alfnes, and co-supervisors Gabriele Hofinger Jünge, Ph.D. and Nina Pereira Kvadsheim, Ph.D for their comments, knowledge and help while working on this master thesis. I would also like to thank the case company representatives for their contribution and willingness to support this final part of my master's degree. Lastly, I would like to thank my family and friends for their endless support and encouragement throughout my five years at NTNU.

Trondheim, June 15th, 2023

Hedda Constance Høgseth

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Abbreviations

3D	Three-dimensional
AI	Artificial intelligence
AR	Augmented Reality
ATO	Assemble-to-order
CAD	Computer-aided-design
CAE	Computer-aided-engineering
CE	Circular Economy
CEAP	Circular Economy Action Plan
CODP	Customer order decoupling point
CPS	Cyber-Physical Systems
DTs	Digital technology
DTs	Digital technologies
EOL	End-of-life
ERP	Enterprise resource planning
ETO	Engineer-to-order
EU	European Union
I4.0	Industry 4.0
I5.0	Industry 5.0
IoT	Internet of Things
IT	Information Technology
MES	Manufacturing execution system
MP	Mass produced
MTO	Make-to-order
MTS	Make-to-stock
OKP	One-of-a-kind production
PLM	Product lifecycle management
RFID	Radio frequency identification
RPA	Robotic process automation
TRL	Technology readiness level
VR	Virtual Reality
UAE	United Arab Emirates

1 Introduction

In this section, an introductory overview of the research area of interest is provided, beginning with its research background. The research objectives and questions are subsequently defined to guide the investigation, followed by the argumentation of the research scope of this thesis. Additionally, an outline of the sections comprising this thesis is presented.

1.1 Background

The world is facing severe environmental damage due to the rapid consumption of the earth's natural resources, causing an increase in waste generation and resource scarcity (Bhatia et al. 2022). Given these factors, the need for pursuing new sustainable business approaches has become paramount (Jünge 2022) and can be addressed by applying the principles of circular economy (CE), in which "the industrial system is restorative or regenerative by design" (Kok et al. 2013; MacArthur and Waughray 2016). As of recent, The European Commission adopted the new Circular Economy Action Plan (CEAP) in March 2020. It is one of the main building blocks of the European Green Deal and will be Europe's new agenda for sustainable growth. The new action plan announces initiatives along the entire life cycle of products. It targets how products are designed, promotes CE processes, encourages sustainable consumption and aims to ensure that waste is prevented and that the resources used are kept in the European Union (EU) economy for as long as possible (Commission 2020a). A CE would turn goods at the end of their service life into resources for others, closing loops in industrial ecosystems and minimizing waste. The increasing sustainability concerns have resulted in a wish to replace the current production and consumption system – take-make-dispose linear model (Tonelli and Cristoni 2018; MacArthur et al. 2013) with a make-remake-use-return principle (Kvadsheim et al. 2019; Goltsos et al. 2019; Parida et al. 2019). The implementation of CE logic will replace production with sufficiency: reuse what you can, recycle what cannot be reused, repair what is broken, and remanufacture what cannot be repaired (Stahel 2016).

To transition from a linear supply chain to a CE, tackling the end-of-life (EOL) phase is critical to achieving sustainability and moving towards a CE (Jo Wessel Strandhagen et al. 2022). Remanufacturing is considered one of the most effective and efficient EOL strategies of the circular economy, in terms of environmental benefits and economic viability (Lahrour et al. 2019). It involves the remanufacture and reuse of EOL products and components, thus extending their useful life and reducing the demand for virgin materials. Despite the potential benefits of remanufacturing, adopting such reverse flow strategies is a complex process. Many uncertainties arise when a linear supply chain is replaced with a circular one with a reverse flow of goods, parts, and materials (Simonetto et al. 2022, Battini et al. 2017).

The sustainability focus has also affected the industry (Para-González et al. 2020; T. Lee and H. Nam 2017; Jo Wessel Strandhagen et al. 2022), and stakeholders need to investigate how their operations can become greener and more socially responsible. (Jo Wessel Strandhagen et al. 2022). For the maritime industry, sustainability means new and more efficient solutions for operations and supply chain management to be economically profitable and satisfy sustainability's social and environmental dimensions (Jo Wessel Strandhagen et al. 2022). To meet the goals of CEAP, maritime manufacturers need products with reduced environmental impact and lower emissions, involving components for a prolonged lifetime (Jansson 2016). CE strategies such as remanufacturing support the goals of the CE and are ways to prolong the lifetime of a marine structure (Jansson 2016). Shipbuilding and production of maritime products are the most complex type of Engineer-to-order (ETO) and involve the production of large, highly customized, and complex products (Willner et al. 2015). In the maritime industry, the term CE is not well-established and needs scientific support to "close the loop", minimize waste and increase revenue streams (Okumus et al. 2023).

This transition process will need new technology (Stahel 2016). Whilst having significant potential to improve industrial performance (Dalenogare et al. 2018), digital technologies (DTs) will also be a critical enabler for the CE by tracking the flow of products, components and materials and making the resultant data available for improved resource management and decision-making across the various stages of the supply chain (Kristoffersen 2021; Sousa Jabbour et al. 2018). Technology, such as the Internet of Things (IoT), digital twin and big data, will boost shift and unlock the circularity of resources within the supply chain (Aldrighetti et al. 2022). ETO companies in the maritime industry are lagging behind other industries in manufacturing regarding digitalization (Jo Wessel Strandhagen et al. 2022). Some recommendations have been proposed (Jo Wessel Strandhagen et al. 2022; Antikainen et al. 2018; Okumus et al. 2023, Jabbour et al. 2019). However, there is still not clear to many in either the industry or research how DTs can aid companies in improving CE functioning and supporting the transition from a linear supply chain (Antikainen et al. 2018).

This thesis aims to address a critical gap in the maritime industry by first understanding which factors determine the potential for remanufacturing a used product, and which uncertainties implementing remanufacturing will bring to a supply chain. Further DTs will be discussed as a measure to overcome these uncertainties and consequential support the integration of such CE strategies. This is achieved through a case study of the maritime industry and is complemented by relevant literature on maritime supply chains, ETO manufacturing, CE, and DTs. The study sets out to contribute to the literature on understanding how maritime ETO companies can evolve with the increasing focus on CE and integrate remanufacture into their operations.

1.2 Research scope

This section will define the area of interest and boundaries of this thesis. Scoping the focus of this thesis will help ensure that the research is focused, relevant and achievable within the time frame.

The thesis focuses on two aspects: firstly, the evaluation of product-level factors that determine the potential for remanufacturing a used product, and secondly, an analysis of the uncertainties that arise at the supply chain level due to remanufacturing. The decision to differentiate between these two parts is aimed at to understand the enabling factors of remanufacture on a product level and to get a more holistic perspective on which supply chain uncertainties that must be addressed to facilitate the successful integration of remanufactured products into an ETO supply chain.

1.2.1 Engineer-to-order

The scope of this research is confined to ETO companies that offer customized products. Focusing on ETO companies, the overall aim of this thesis is to contribute to the understanding of ETO companies to how they can potentially integrate remanufacture as a CE strategy in their supply chain with the aid of DTs.

To be clear, this thesis does not discuss the practicalities of how an ETO company can establish such a strategy, but rather which product factors and supply chain uncertainties they should be aware of when it comes to remanufacturing used products. Even though it is essential to understand the practicalities of integrating such strategies, it falls outside the scope of this thesis.

To establish a basis for the current linear ETO supply chain, the shipbuilding supply chain presented by Jo Wessel Strandhagen et al. 2022 was used. The decision to use this as a base is justified by the fact that for the interview findings to be relevant, a study of a supply chain similar to which they operate made sense. This supply chain is divided into five phases; design, supplier and logistics, manufacturing and assembly, product use, and EOL. The product use and EOL phase falls within the scope of this study. This is because these phases are at the final stages of a product life cycle. How an ETO company handles these processes is critical to achieving sustainability and moving towards a CE (Jo Wessel Strandhagen et al. 2022).

To categorize the supply chain uncertainties identified by the case companies during interviews. The supply chain uncertainty circle developed by Mason-Jones and Towill 1997 will be used. This model differentiates between four sources, namely supply, process, demand and control. Even though the model has been subsequently refined and applied in a number of different ways, with Peck and Juttner 2002 introducing exogenous events and Sanchez Rodrigues et al. 2008 incorporating the transport uncertainty, these have not yet been applied in any project industries (Gosling, M. Naim et al. 2013). Therefore, these additional sources will not be considered in this research.

1.2.2 Circular Economy

To narrow down the broad scope of the CE, by the definition of MacArthur and Waughray 2016, this thesis focuses on the technical pathway of the CE. Here, the motivation is to keep products at their highest value and then cascade into reusing by feeding used products and components into the supply chain. The primary objective is to retain products at their maximum value and facilitate their reuse by reintroducing used products and components back into the supply chain. It should be noted that this study will not encompass the biological aspect of the CE definition. Furthermore, the focus of this research will be mainly on the circular strategy of remanufacturing. This specific strategy has been selected because, as stated in MacArthur and Waughray 2016, the materials used for recycling possess value, but the highest value is attributed to the products derived from these materials. Therefore, investigating this aspect of the CE concept is likely to be the most interesting.

The CE operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond) (Kirchherr et al. 2017; MacArthur et al. 2013). Due to the fact that the companies interviewed in the empirical part of this research are industrial companies one can argue that these companies operate at both micro and meso levels of the CE. At the micro level, individual ETO companies can implement CE principles and practices, such as the use of recycled materials, and designing products for reuse, repair, or remanufacturing. This research focuses on exploring opportunities at the micro level while acknowledging that integrating CE strategies into the ETO companies' supply chain will have meso level consequences due to their vast supplier networks. However, these considerations will not be included in this thesis.

1.2.3 Digital technologies

By scoping the thesis with the term DTs, this research will be able to explore the technical aspects of Industry 4.0 and examine how these technologies can aid in integrating circular strategies such as remanufacturing. Although an Industry 5.0 term was introduced in 2021 by the European Commission, the term is not a chronological continuation of the existing I4.0 paradigm and considers a more value-driven approach to the implementation of technologies (Xu et al. 2021). Thus the term is detached from the scope of this thesis which is focused on the technical solutions I4.0 technology brings. While the human-centric approach of Industry 5.0 is important, focusing on the technical aspects of Industry 4.0 will provide a solid foundation for understanding how DTs are changing the manufacturing industry and how ETO companies utilize DTs to their advantage without considering human factors.

1.3 Purpose and research questions

1.3.1 Purpose

The aim of this study is to explore the potential for transitioning ETO supply chains towards a CE and investigate how DT can support the integration of remanufacturing within these supply chains. The study seeks to obtain a comprehensive understanding of the factors that enable remanufacturing for ETO products, as well as how DTs can address the uncertainties within the supply chain, thereby facilitating the effective implementation of remanufacturing practices.

Building on the research scope in Section 1.2 and the abovementioned aim of this thesis, three objectives and four respective research questions (RQ) were formulated to guide the research and to get a clear view of the field of interest. The RQs and objectives are summarized in Table 1.

1.3.2 Research questions and objectives

Objective 1: Perform a state-of-the-art analysis of digital technologies within an ETO context, with emphasis on the practice of remanufacturing.

A state-of-the-art analysis of existing literature on ETO companies and non-repetitive manufacturing will give an overview of circular strategies in an ETO environment with the main focus being remanufacturing. Further, get an overview of which DTs are fit for ETO and remanufacturing. This will enable me to answer the first question.

RQ1: *Which digital technologies are suited for remanufacturing in an ETO environment?*

Objective 2: Conduct semi-structured interviews in order to examine the variables that influence the potential of remanufacturing, as well as to gain insight into the uncertainties involved in incorporating such a strategy within an ETO supply chain.

It became clear that further investigation into the ETO environment was needed. Thus, a case study in the form of semi-structured interviews with ETO companies from the maritime industry was conducted. The motivation for the case study was to understand which factors ETO companies see as crucial when determining whether to remanufacture or not, and which supply chain uncertainties remanufacturing brings. The findings from semi-structured interviews and following questionnaire will be used to answer research questions 2.1 and 2.2, and learnings from the interviews will be the basis for meeting objective 3.

RQ2.1: *Which factors determine the potential of remanufacturing in an ETO environment?*

RQ2.2: *Which supply chain uncertainties must ETO companies face when integrating* *remanufacturing practices?*

Objective 3: Contributes to understanding how digital technologies can address uncertainties in integrating remanufacturing into an ETO supply chain, and provide insights into the effective utilization of digital tools for managing uncertainties in this context.

By analyzing relevant literature and data obtained through semi-structured interviews, the study will explore which DTs can aid the integration of remanufacturing and how they can address the supply chain uncertainties associated with remanufacturing.

RQ3: How can digital technologies address the uncertainties associated with the integration of remanufacturing to an ETO supply chain?

Table 1: Summary of research questions and objectives

Research question	**Objectives**
RQ1: Which digital technologies are suited for remanufacturing in an ETO environment?	Perform a state-of-the-art analysis of digital technologies, within an ETO context, with emphasis on the practice of remanufacturing.
RQ2.1: Which factors determine the potential of remanufacturing in an ETO environment? **RQ2.2:** Which supply chain uncertainties must ETO companies face when integrating remanufacturing into an ETO supply chain?	Conduct semi-structured interviews in order to examine the variables that influence the potential of remanufacturing, as well as to gain insight into the uncertainties involved in incorporating such a strategy within an ETO supply chain.
RQ3: How can digital technologies address the uncertainties associated with the integration of remanufacturing to an ETO supply chain?	Contributes to understanding how digital technologies can address uncertainties in integrating remanufacturing into an ETO supply chain, and provide insights into the effective utilization of digital tools for managing uncertainties in this context.

1.4 Research development

Figure 1 provides a comprehensive illustration of the research progression undertaken in this study. The diagram outlines the initial stages, including a specialization project undertaken at NTNU in the autumn of 2022, and a preliminary literature study, which together formed the foundation of the research. This was then developed into the research objectives, questions, and scope, which led to the implementation of a literature study and a case study. The insights derived from the theoretical findings served as the base for the discussion and conclusion of this master thesis.

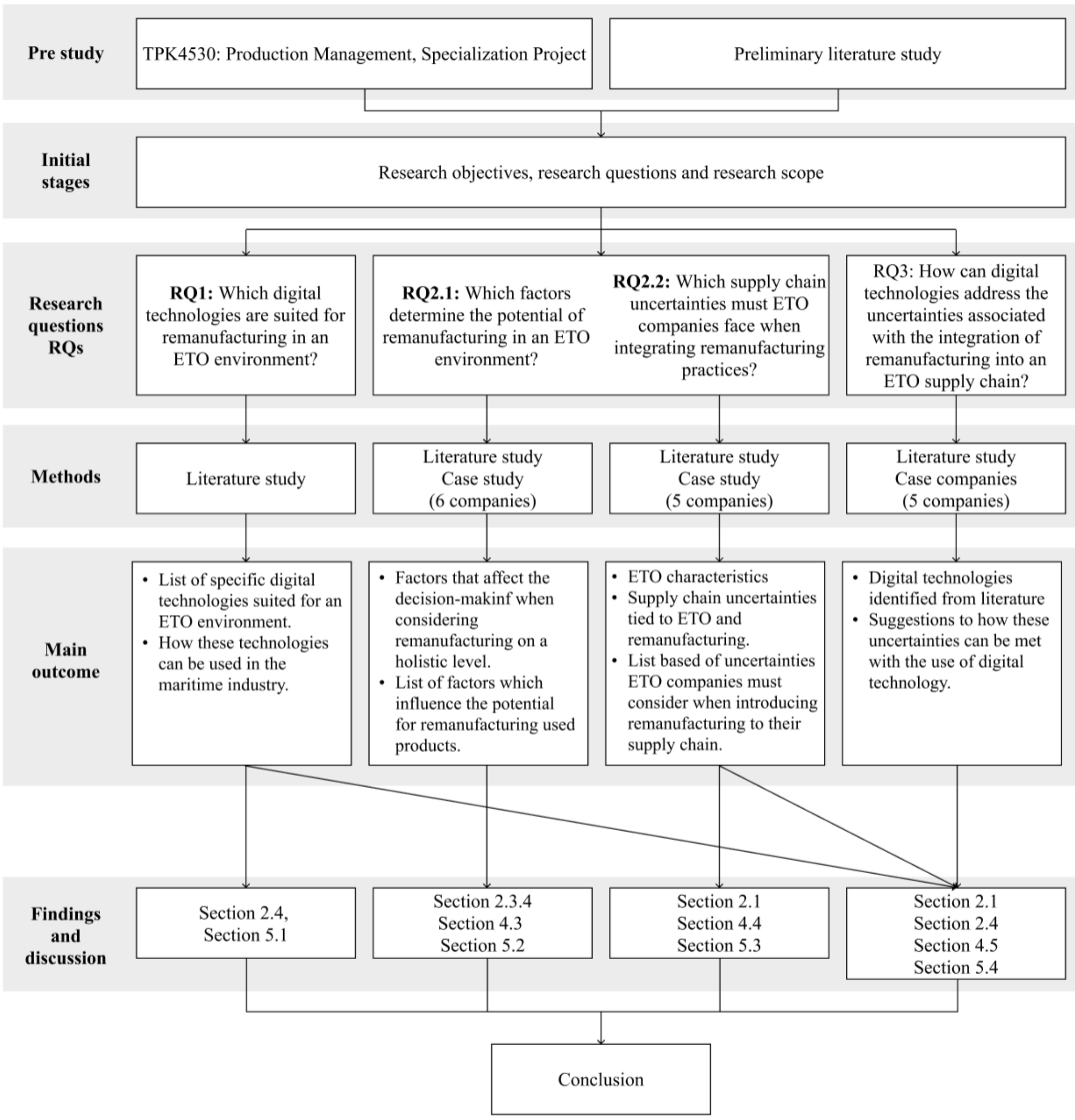

Figure 1: Research development of master thesis, own production

1.5 Research outline

In this section, you will receive a brief introduction to the chapters of this thesis, providing you with an overview of the entire study.

Chapter 1: Introduction
The introduction briefly presents the background, the research objectives, the research question, and the scope and structure of this report.

Chapter 2: Theoretical background
In this section, the introduction to the relevant topics of this thesis will be introduced. First, the maritime industry and ETO manufacturing will be introduced, then the CE with emphasis on remanufacturing, and lastly the DTs will be presented to provide the reader with an overview of the topics of the entire study.

Chapter 3: Methodology
The methodology section of the report outlines the research methods employed, including the literature study and case study. Additionally, it justifies the choice of research methods and presents the limitations of the chosen methods.

Chapter 4: Case study findings
This section presents the analyzed case studies conducted as part of this study. Each case study begins with a brief introduction of the company, followed by its current circular strategies. Furthermore, the section outlines the key factors identified by the company as crucial in determining the potential of remanufacturing and highlights any uncertainties that need consideration when incorporating remanufacturing into their supply chain.

Chapter 5: Discussion
The discussion uses findings to answer the research question; and discusses the implications and interpretations of the results.

Chapter 6: Conclusion
The conclusion summarises the findings of the study, highlights contributions to knowledge and practices, discusses limitations and highlights future research necessity.

2 Theoretical background

The theoretical background introduces the relevant theory within the research scope to provide a basis for the empirical part. This section will serve as the foundation for the development of a solution for implementing remanufacturing in ETO companies. The empirical work will be conducted through a case study and will be combined with the theoretical background to develop the solution.

2.1 Overview of engineer-to-order manufacturing

This section offers an introductory explanation of the important concepts related to ETO and emphasizes the different uncertainties that can arise in managing this type of supply chain.

This thesis focuses on a set of companies operating with an ETO supply chain. Using the definition from Christopher 1992, we define a supply chain as the network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer. There are several types of supply chains and elements that differentiate the types (Adrodegari et al. 2015). The customer order decoupling point (CODP) differentiates four main types of supply chains: make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO), and ETO (Olhager 2003; Mello, Gosling et al. 2017), see Figure 2. In an ETO supply chains, the CODP is located at the design stage in the engineering phase of Figure 2 (Gosling and M. M. Naim 2009). As a result, every individual order is incorporated into the product's design phase, ensuring that each product is tailored to meet the specific requirements of the customer.

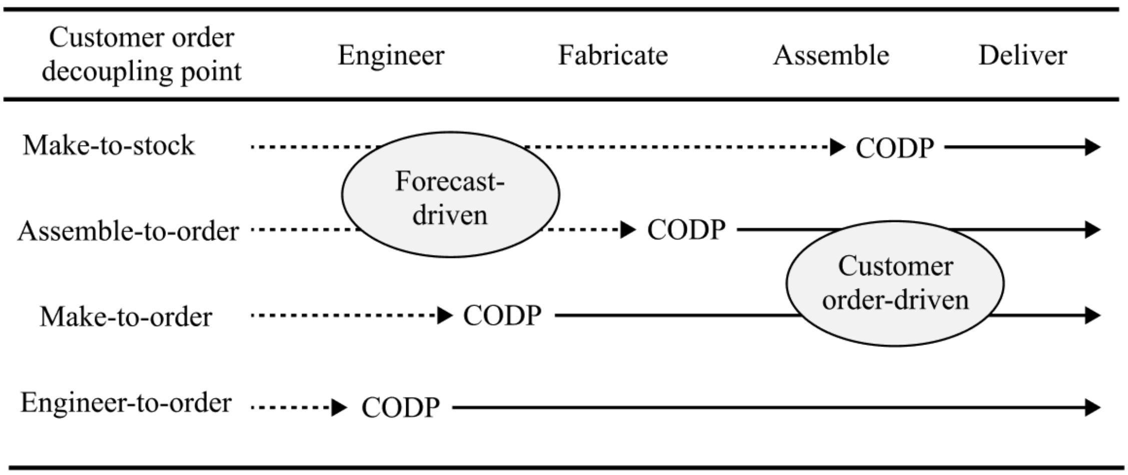

Figure 2: CODP for MTS, ATO, MTO and ETO, adapted by Olhager 2010.

There is a wide diversity of definitions to concretize the term ETO. Porter et al. 1999 defines the term as: "a standard product range is offered with the added availability of modifications and customizations being made to request", while Gosling and M. M. Naim 2009 define an ETO supply chain as a process where production is customized to each order and where the customer participates in the design phase, often operation is in project-based environments. In operations management and in this thesis the definition provided by Reid and Sanders 2019 will be used. They defined engineer-to-order as the production process in which a customized product is designed and manufactured according to a customer's specific requirements.

The ETO supply chain is typically used for products that are customized rather than mass-produced (MP) and relates to companies that are involved in the design and production of customized products such as construction projects (Jo W Strandhagen et al. 2018), mechanical engineering, and shipbuilding (Cannas, Gosling et al. 2019; Cannas and Gosling 2021; Mello, Gosling et al. 2017). Companies operating with an ETO supply chain, referred to as ETO companies, are businesses specializing in creating highly customized products produced on low volumes, which can lead to one-of-a-kind production (OKP) scenarios tailored to specific customer requirements (Gosling and M. M. Naim 2009; Powell et al. 2014; Wikner and Rudberg 2005; Olhager 2003). The ETO supply chain includes both non-physical and physical stages of production (Bertrand and Muntslag 1993; Wikner and Rudberg 2005; Adrodegari et al. 2015). The non-physical step comprises tendering, design, and process planning, while the physical stage includes component manufacturing, assembly, and installation (Adrodegari et al. 2015; Gosling and M. M. Naim 2009; Wikner and Rudberg 2005).

Unlike other manufacturers, ETO companies prioritize customization, requiring a high level of flexibility in the manufacturing process (Olhager 2003). Their success depends on engineering expertise, as complex and innovative solutions are often required to meet customer needs (Powell et al. 2014). ETO companies typically work project-based, necessitating strong project management skills to ensure timely, on-budget delivery that satisfies the customer. However, due to the need to design and engineer each product, ETO companies often have longer lead times and higher costs than other manufacturers (Adrodegari et al. 2015; Willner et al. 2015). To increase cost efficiency, outsourcing has been a major trend for most ETO companies (Mello, Gosling et al. 2017; Hicks, McGovern et al. 2000), with manufacturing activities being preferentially outsourced, except in cases where manufacturing capabilities are necessary due to a lack of potential suppliers (Mello, Gosling et al. 2017). As a result, the ETO supply chain involves a network of multiple companies worldwide to develop and produce high-value products (Gosling and M. M. Naim 2009; Hicks, McGovern et al. 2000; Mello, Gosling et al. 2017). These products make up a multi-component structure of the final products, which consist of both standard and non-standard items (Hicks, McGovern et al. 2000; Olhager 2010). Making some components are needed in low-volumes and others in medium to large volumes (Hicks, McGovern et al. 2000).

Companies operating with an ETO supply chain must consider significant uncertainties regarding product specification, demand composition, supply and delivery lead times, and production processes' duration (Adrodegari et al. 2015; Wikner and Rudberg 2005). The production process for ETO companies can be highly variable, with different products requiring different processes and workflows, making it challenging to optimize the production process and ensure consistent quality. In addition, due to the low volume and high customization level, benefits such as economies of scale and standardization, usually sought by traditional mass production, are not easily applicable to an ETO strategy (Jo Wessel Strandhagen et al. 2022; Adrodegari et al. 2015). Managing customization requirements in the new product development process presents many difficulties in ETO supply chains (Mello, Gosling et al. 2017). Another challenge is demand irregularity, where demand patterns are inconsistent and competitive bidding can cause delays and problems (Mello, Gosling et al. 2017). More about these uncertainties in Section 2.1.1. Again, this requires a high level of flexibility in the manufacturing processes (Olhager 2003). In conclusion, the characteristics described in this section are essential to understanding ETO companies. Below, you will find the key takeaways listed.

- Low volume
- A high degree of customization
- High demand oscillations
- Products of multi-component structures
- Some standard and some non-standard components
- Large network of suppliers to produce a product
- Long lead times
- High-value products
- Project-based environment
- Customer-specific products
- Highly skilled labour

2.1.1 Supply chain uncertainties in ETO and remanufacturing

As mentioned in the previous section, ETO supply chains are complex systems. Here complexity refers to the interaction among processes, decisions, and structures of the different supply chain actors, which strongly affect the performance of the system (Goltsos et al. 2019). Van Der Vorst and Beulens 2002 defined supply chain uncertainty as,

> Supply chain uncertainty refers to decision-making situations in the supply chain in which the decision-maker does not know definitely what to decide as he is indistinct about the objectives; lacks information about (or understanding of) the supply chain or its environment; lacks information processing capabilities; is unable to accurately predict the impact of possible control actions on supply chain behaviour; or, lacks effective control actions (uncontrollability).

Where uncertainty can be defined as a state that ranges from just short of certainty to a near complete lack of knowledge about a result (Gosling, M. Naim et al. 2013). A core issue for a "traditional" linear supply chain is managing uncertainty (Goltsos et al. 2019). Mason-Jones and Towill 1997 defined an uncertainty circle, where the three types of uncertainties defined by Davis 1993 were further developed to a resulting framework which categorizes supply chain uncertainty into four types: process, supply, demand, and control (Mason-Jones and Towill 1997; Gosling, M. Naim et al. 2013). These four sources of categories will later be used to systematize the sources of uncertainty in remanufacturing. The next section will mention uncertainties tied to both linear supply chain and the supply chain of CE, namely the circular supply chain (CSC). To give context the CSC has two distinct parts, a reverse flow and a forward flow. The forward supply chain is the traditional linear flow of goods from raw materials to finished products, while the reverse supply chain involves the reuse, repair, and remanufacturing of materials and products (Aldrighetti et al. 2022; Farooque et al. 2019).

Supply uncertainty is a type of uncertainty that arises from variations in the availability, quality, or reliability of raw materials, components, or services from suppliers (Goltsos et al. 2019). In a CSC, reverse flow uncertainty tends to be the primary driver of supply uncertainty. These will include, timing, quantity, collection procedures and quality of returned products (Zeballos et al. 2012).

Process uncertainty is the type of uncertainty that arises from variations in the performance or output of production processes. Examples include breakdowns, quality defects, or variations in production speed (Goltsos et al. 2019). The primary difference between process uncertainties in a CSC compared to a linear supply chain is that a CSC involves more complex and diverse processes that involve multiple material flows and product life cycles. This means that the sources of uncertainty are similar in linear and CSCs, however, the CSC often displays a greater level of severity (Goltsos et al. 2019).

Demand uncertainties arise from variations in the level and pattern of demand for products

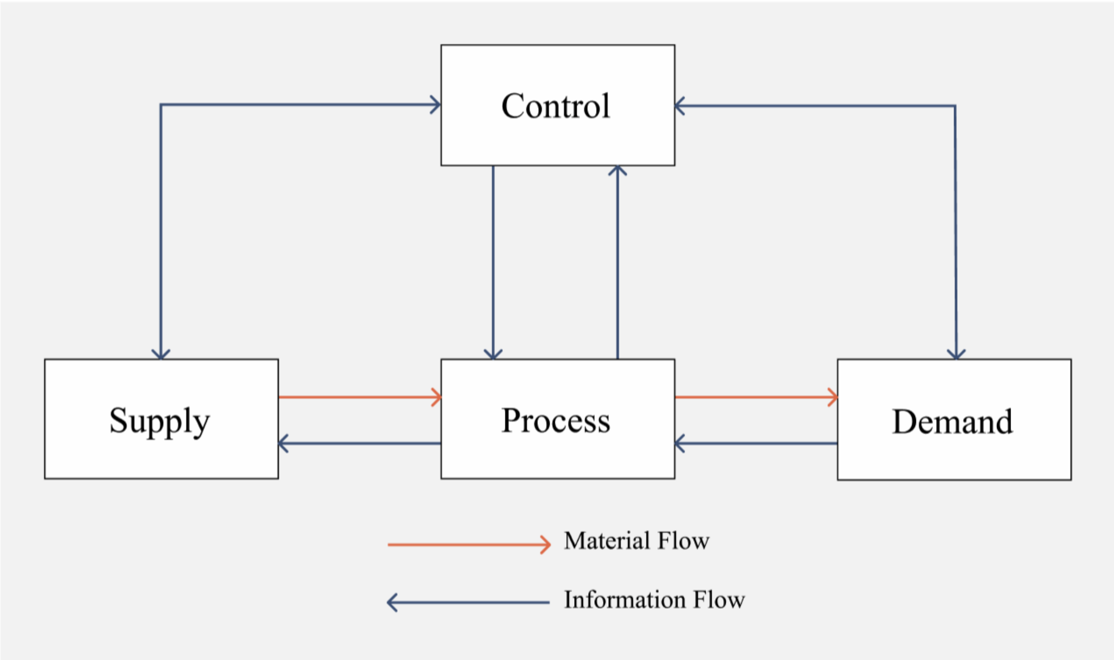

Figure 3: The supply chain uncertainty circle, adapted by Boehme 2009.

or services. Examples include changes in customer preferences, market trends, or unexpected events, which can lead to uncertainties in quantity, timing and location and product specification (Goltsos et al. 2019). In the shipbuilding industry, the market is volatile and heavily dependent on macroeconomic factors so sudden changes in demand are expected.

Control uncertainties arise from variations in the ability of the organization to manage and control its operations. Examples include delays, errors, or communication breakdowns within the organization. This type of uncertainty often occurs from our attempts to manage the uncertainties originating from supply, process, and demand (Mason-Jones and Towill 1997). In Figure 3 the dynamics of these supply, process, demand and control are visualized. The strategies used to manage these uncertainties, such as forecasting procedures, inventory policies, and information sharing, contribute to control uncertainty (Goltsos et al. 2019).

The focus of this thesis is how remanufacturing can be integrated into the ETO supply chain. Articles that discuss the uncertainties associated with these strategies for CE and ETO supply chains were examined. The authors Gosling, M. Naim et al. 2013 conducted a study on uncertainties in the ETO construction supply chain and classified them. Due to the similarities between the construction and maritime industries (Jo W Strandhagen et al. 2018; Cannas, Gosling et al. 2019; Mello and J. O. Strandhagen 2011), both characterized by high levels of customization and project-specific designs, we will utilize the insights obtained from this study, along with the remanufacturing-related uncertainties identified by Goltsos et al. 2019, as a foundation to define Table 2.

Table 2: Uncertainties found in ETO supply chains with remanufacturing practices.

Uncertainty source	Uncertainty	
Supply	Raw material availability	Quality of used products
	Supply lead time (schedule adherence)	Collection procedure
	Used product availability	Transportation lead time
	Variation in quality level of used product	
Process	Yield and quality	Labour resources
	Processing times	Change in production
	Machine availability	Lack of knowledge
	Batching rules	
Demand	Quantity	Change in customer preferences
	Timing	Economic downturn
	Locations	Market competition
	Product specification	Product cannibalization
	Customer quality requirement	Customer perception (new/used)
Control	Stock control policy	Legislation and restrictions
	Forecasting method of returned products	Remanufacture planning with supplier network
	Capacity planning decisions	Lack of control of the processes (new/used)
	Accuracy of assessment of used product	Economic feasibility of remanufacturing

Goodall et al. 2015 article on remanufacturing identified a key factor that complicates remanufacturing decision-making compared to traditional linear manufacturing supply chain as the high level of uncertainty associated with the return of used products. The article mentions the lack of information flow between early life cycle phases, specifically the product use phase, and the manufacturer as the reason for this key uncertainty. Further, Goodall et al. 2015 mentions that the amount of information feedback throughout a product's useful life will significantly affect the uncertainty at the remanufacturing stage.

The uncertainties in Table 2 will later be used in the case study to identify the specific uncertainties that the maritime companies are concerned with when it comes to integrating remanufacturing. These uncertainties identified will then in Section 5.4 be discussed as a tool for minimizing the uncertainties that remanufacturing brings.

2.2 The maritime industry

This section presents a study of the maritime industry, which includes a categorization of the maritime actors along with their characteristics and interrelationships.

Mellbye, Theie et al. 2015 defined the maritime industry as comprising all businesses involved in owning, operating, designing, building, and supplying equipment or specialized services to various types of ships and other floating entities. The authors also specify that firms generating over 50% of their turnover from maritime activities are considered part of this industry. The maritime industry operates on a global level and serves as a critical facilitator of trade and transportation across diverse sectors. Among the assets within the maritime industry, vessels hold significant importance due to their role in merchant shipping and related activities (Milios et al. 2019).

2.2.1 Actors in the maritime industry

Jakobsen 2011, identified four primary categories of maritime activities in which firms can engage. These four categories of maritime companies are either shipyards, shipping companies, maritime equipment suppliers or maritime service providers. Some researchers, such as Mello, Gosling et al. 2017, have expanded the scope of maritime actors beyond the four main categories of shipping firms, shipyards, suppliers of maritime equipment, and providers of maritime services. Mello, Gosling et al. 2017 identified shipowners, ship designers, main equipment suppliers, and other suppliers as the main actors in the maritime industry (Jo Wessel Strandhagen et al. 2022.). In this thesis, we will look at the four primary categories provided by Mellbye, Theie et al. 2015. In the next section, we will discuss the different players in the maritime industry and how they are connected to each other.

Building on the definition provided by Jakobsen 2011, shipping companies primarily own and/or operate vessels that can be tailored to fulfil the demands of other maritime actors. These companies are usually categorized into four segments: offshore, drilling and production, deepsea, and shortsea. While these categories will not be further elaborated here, a more comprehensive introduction to shipping companies can be found in Jakobsen 2011. Shipyards can be classified into two main disciplines: the construction of new vessels and the maintenance, repairs, and modifications of existing ones (Jakobsen 2011). Shipyards rely heavily on shipping companies since their operations are predominantly fueled by requests from them.

In order to meet the needs of shipping companies, the presence of maritime equipment suppliers is crucial (Jakobsen 2011). These suppliers can be categorized into three main segments, as described by Mellbye, Theie et al. 2015: mechanical equipment, electrical and electronic equipment, and other operating equipment. The mechanical equipment category includes suppliers of engines, propellers, cranes, and winches. The electrical and electronic equipment segment encompasses specialist hardware, software, electrical propulsion systems, bridge equipment, and dynamic positioning systems. Lastly, the other operating equipment segment consists of marine paint, lubricants, lifeboats, cables, chains, and other supplies used for the everyday operations of ships (Jakobsen 2011).

Maritime service providers become essential as ships start operating, driven by the demand from shipping companies. These services fall into four segments: financial and legal, technological, port and logistics, and trade. Financial and legal services are dominated by financial institutions, brokers, lawyers, and insurance companies. Technological services include classification, engineering, ship design, and installation work. Included in this section are the maritime classification societies. Port and logistics services focus on port facilities, supply bases, loading and unloading, and air transportation for ships and rigs. Trade services encompass wholesale and retail companies that offer marine equipment (Jakobsen 2011).

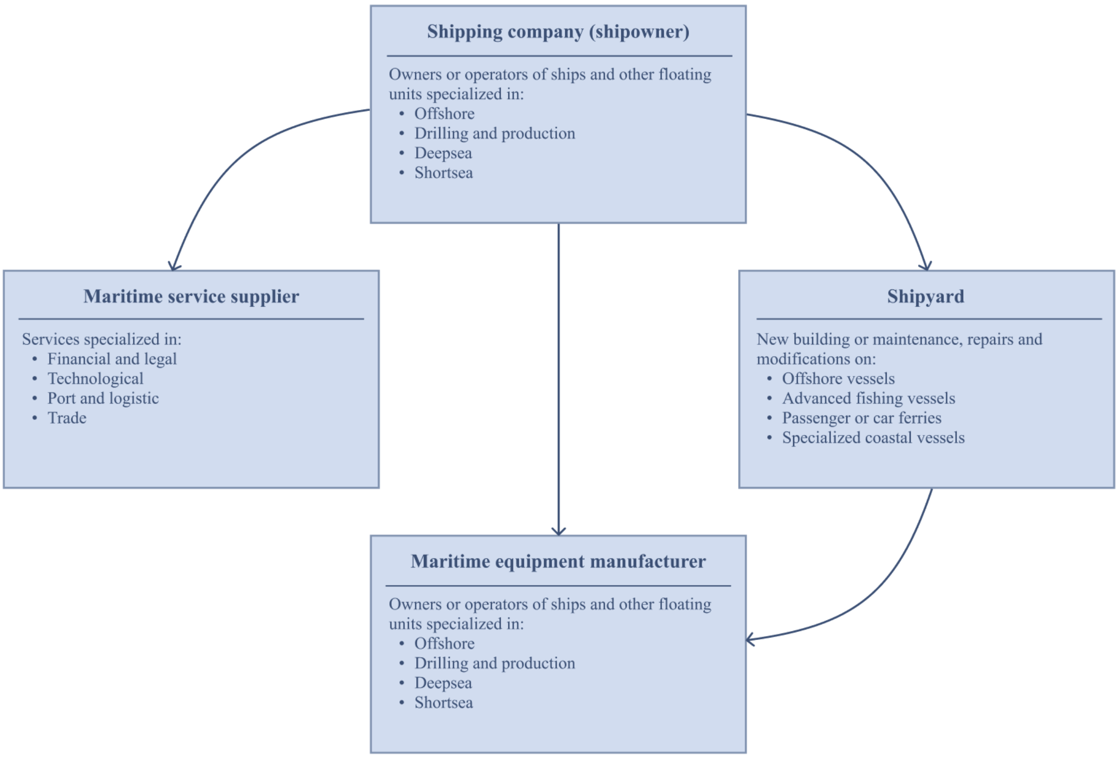

Figure 4: Stakeholders in the maritime industry, adapted by Jakobsen 2011.

2.2.2 Characteristics of a maritime supply chain

In this thesis, we will explore the technological services, more specifically the classification societies. These societies establish and publish rules (technical and administrative) for ships in the project phase, under construction or operation (Fulconis and Lissillour 2021), and therefore have a dual mission of classifying and certifying ships. In the Norwegian maritime program called Maritim21 a key driver for the maritime industry was identified to be regulations (Mellbye, Rialland et al. 2016). These regulations imposed by national and international governments play a significant role in shaping the development of solutions within the maritime industry (Mellbye, Rialland et al. 2016). These regulations can take the form of mandatory requirements enforced by law or incentives provided through subsidies and grants.

While classification societies are not governmental entities themselves, they operate in close collaboration with national and international governments to ensure compliance with laws and regulations. The maritime industry is subject to a complex framework of regulations imposed by various governing bodies. Classification societies act as key intermediaries between ship owners, shipbuilders, and regulatory authorities. They work closely with these stakeholders to ensure that ships adhere to the relevant regulations and standards (Fulconis and Lissillour 2021). Classification societies develop their rules and guidelines based on the internationally agreed standards established by the IMO and other regulatory bodies (International Association of Classification Societies (IACS) 2022). The four groups are reliant on each other as they create a demand for other business areas and provide necessary services to other maritime players. An overview of the actors and how they interact can be found in Figure 4.

The maritime supply chain involves the production of ships and other maritime products. As the maritime industry of Western Europe produces more sophisticated and tailored ships, this industry can be generically identified as ETO(Mello and J. O. Strandhagen 2011). From the perspective of operations and supply chain management, the production of these products is the most complex type of ETO and involves complex products that require thousands of engineering hours (Willner et al. 2015; Jo Wessel Strandhagen et al. 2022; S. Nam et al. 2018). Maritime ETO companies include the production of customized ships and other maritime products tailored to meet specific customer requirements.

The production process in a maritime supply chain is characterized by a high level of labour intensity, as it involves a wide variety of skilled labour and is typically non-repetitive (Bertrand and Muntslag 1993; Jo Wessel Strandhagen et al. 2022; Powell et al. 2014; J. Strandhagen et al. 2019). It is not only the variety in skilled labour and product configuration that will change depending on the customer's requirements but also the market as a whole can dramatically change (Adrodegari et al. 2015). The market that maritime ETO companies operate within can be exceptionally volatile, meaning that the market can experience periods of unpredictability and sharp price movements (Mellbye, Theie et al. 2015). The production of these products is also marked by a high level of uncertainty, as the product requirements are often defined in the early stages of a project but are subject to iterative changes as the project progresses (Bertrand and Muntslag 1993; Hicks, Mcgovern et al. 2001; Jünge 2022). This uncertainty makes it difficult for ETO companies to forecast demand, order materials accurately, and produce products in advance (Bertrand and Muntslag 1993).

One of the key challenges in producing maritime ETO products is the short delivery times that are often required by customers (Jünge 2022). This results in an intensive production period in which manufacturers must work quickly to complete the product to minimize the earning opportunities lost while the ship is unable to generate sales. To meet these tight deadlines, ETO companies must have a responsive supply chain that is flexible enough to accommodate changes in customer requirements (Olhager 2003).

The production of maritime ETO products is typically characterized by a low level of automation, as the industry relies heavily on manual labour (Sjøbakk et al. 2014; Jo Wessel Strandhagen et al. 2022). This is due in part to the fact that the benefits of economies of scale and standardization are not easily applicable in this manufacturing (Jo Wessel Strandhagen et al. 2022). As a result, the degree of automation in the maritime industry is limited compared to other manufacturing sectors (Para-González et al. 2020). The production of maritime ETO products also involves a wide variety of products, including both large ships and smaller components and work objects (Bertrand and Muntslag 1993; Jo Wessel Strandhagen et al. 2022). This requires a high level of coordination and collaboration between the wide network of stakeholders in the supply chain. The engineering and fabrication of these products are often geographically separated, making communication and coordination more difficult.

For maritime ETO companies to work towards more sustainability, a large focus on handling EOL phases of a product's life and understanding how to prolong their life cycle, and ultimately, becoming more circular in their supply chain is crucial (Jansson 2016). To structure the phases of the current linear maritime supply chain, the shipbuilding supply chain defined by Jo Wessel Strandhagen et al. 2022 in combination with Goltsos et al. 2019 linear supply chain will be used as a basis and tool for visualisation see Figure 5. This involves five phases; design, supplier and logistics, manufacturing and assembly, product use and product EOL. As indicated within the defined research scope of this thesis, the primary focus shall be directed towards the final stage of the supply chain, namely product use and the EOL phase.

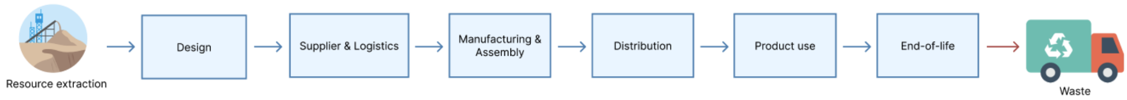

Figure 5: An maritime linear ETO supply chain, adapted from Jo Wessel Strandhagen et al. 2022 and Goltsos et al. 2019
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The operational phase of a ship's lifecycle is the most energy-intensive and contributes to marine pollution and emissions, making it a crucial focus for assessing the sustainability of the maritime industry (Ang et al. 2017; Jo Wessel Strandhagen et al. 2022). This phase starts as soon as the product is set to use by the customer. During this phase, the type of fuel used by the ships and their energy efficiency are key considerations (Jo Wessel Strandhagen et al. 2022). In contrast to products in other sectors, vessels are characterized by a long operation lifespan, traditionally around 20-25 years (Milios et al. 2019; Hiremath et al. 2014).

The end-of-life phase of a ship commences once it is taken out of active service. It signifies the initiation of the final stages of the ship's life cycle within the linear supply chain, as the ship's operational phase concludes and preparations for subsequent phases commence. Companies produce products which are sold to customers, are used and serviced, and then retired (through recycling, reuse, remanufacturing or disposal (N. Nasr and Thurston 2006). The growing annual count of decommissioned ships, combined with the inadequate state of the ship recycling industry, underscores the importance of this phase in attaining sustainability and transitioning to a CE (Jo Wessel Strandhagen et al. 2022; Alcaide et al. 2017).

2.3 Circular Economy and Remanufacturing

This section provides an overview of the CE concept, encompassing a concise introduction to key strategies such as reuse, repair, remanufacture, and recycle. Further, the focus shifts towards remanufacturing, with a specific emphasis on its application within the maritime industry. Drawing insights from existing literature, this section further explores the factors that influence the potential for remanufacturing in this industry context.

2.3.1 Circular Economy

The current linear economy of "take-make-dispose" is characterized by the presence of waste: cases where components, products and materials reach their EOL. In this thesis, waste is defined as material stocks whose value has been temporarily lost due to the lack of a process to restore its value (Blomsma 2018; Marsh et al. 2022). In recent years, to address the faults of the linear model and contribute to sustainable development, a growing interest in the concept of a CE has emerged (Kristoffersen 2021; Blomsma and Brennan 2017; MacArthur et al. 2013; MacArthur and Waughray 2016). While the origin of the CE is not clearly proved (Winans et al. 2017), the mainstream concept of CE was presented in the report entitled "Towards the Circular Economy", the report showed the advantages of a circular business model and the pathways and action for moving towards a CE (MacArthur et al. 2013).

The CE aims to create an industrial economy that is restorative, relies on renewable energy, minimizes the use of toxic chemicals, and eliminates waste through careful design (MacArthur et al. 2013; MacArthur and Waughray 2016). Achieving the aims by maintaining products, components and materials at their highest utility and value constantly, by performing activities for narrowing, slowing and closing material and energy flows (Bocken et al. 2016; Kristoffersen 2021). These activities will be elaborated on in section 2.3.2.

Despite the growing attention and interest in the concept of CE, it is still in its early stages of development, and international standards have only recently begun to emerge (*ISO/TC 323 Circular economy* n.d.; Kristoffersen 2021). Consequently, a comprehensive definition of CE is not yet available in the literature (Jabbour et al. 2019; Kirchherr et al. 2017). Kirchherr et al. 2017 conducted an analysis of 114 definitions and proposed a definition of CE as,

> An economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.

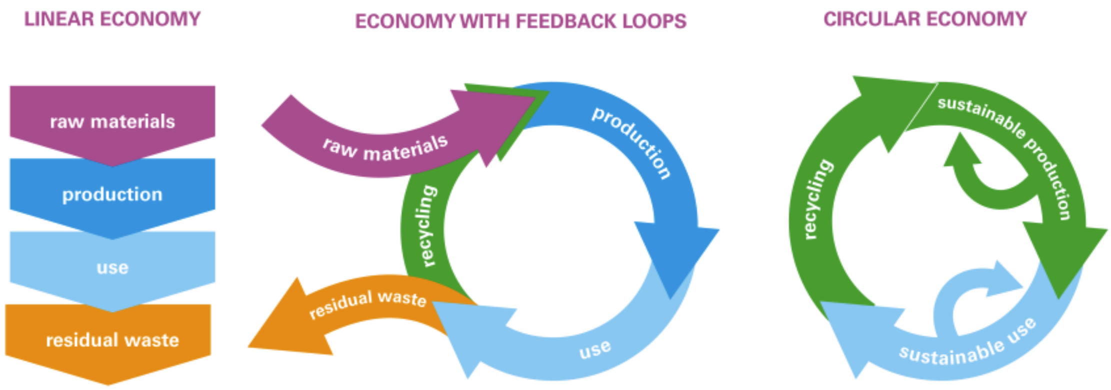

Figure 6: The transition from a linear economy to a circular economy (Zuidema 2015).

Thus, the definition of CE can be considered as a concept that encompasses various subconcepts, highlighting a shared feature of circular strategies that create more value (MacArthur et al. 2013, Kristoffersen et al. 2020).

The concept of a CE has recognized the potential for economic, environmental and social benefits (Fraser et al. 2023, Initiative et al. 2021). However, despite this recognition, the adoption of circular strategies by the industry has been limited so far (Fraser et al. 2023; Initiative et al. 2021). This is a typical progression for transformative ideas, where attention shifts from recognizing the potential to developing frameworks, tools, methods, and approaches to operationalize the concept (Kristoffersen 2021). In McKinsey's article on "The "how" of transformation", the article state that the most difficult part of a transformation is not determining what to do but rather how to do it (Bucy et al. 2016). Currently, there are a variety of frameworks that can potentially support the vision of a CE. Circular strategies frameworks, such as the ReSOLVE framework (MacArthur et al. 2013), Cradle to Cradle (McDonough and Braungart 2010) and The Performance Economy (Stahel 2010). More recently the focus has been on developing a CE transition methodology, which includes aspects such as business models (Kvadsheim et al. 2019), products design, supply chain management (Battini et al. 2017), value chain innovation and other organizational aspects such as human factors, decision-making processes and technology (Antikainen et al. 2018; Aldrighetti et al. 2022). These frameworks will further our knowledge on not what to do to transition from a linear to a CE, but rather how to do it.

2.3.2 Circular strategies

This thesis will primarily concentrate on one strategy associated with CE, namely, remanufacturing. As explicitly stated in the introduction, reuse, repair and recycling will not be the focus of this study, and hence, it will not be extensively explored in the literature study. However, while examining the literature on remanufacturing, it is inevitable to discuss these three strategies. Additionally, to provide context and enhance the reader's comprehension of CE, the thesis will define the four strategies reuse, repair, remanufacture and recycle. This will enable the reader to distinguish between the various circular economy strategies. Furthermore, since the objective is to remain applicable to ETO companies in the maritime sector, examples from this industry will be highlighted.

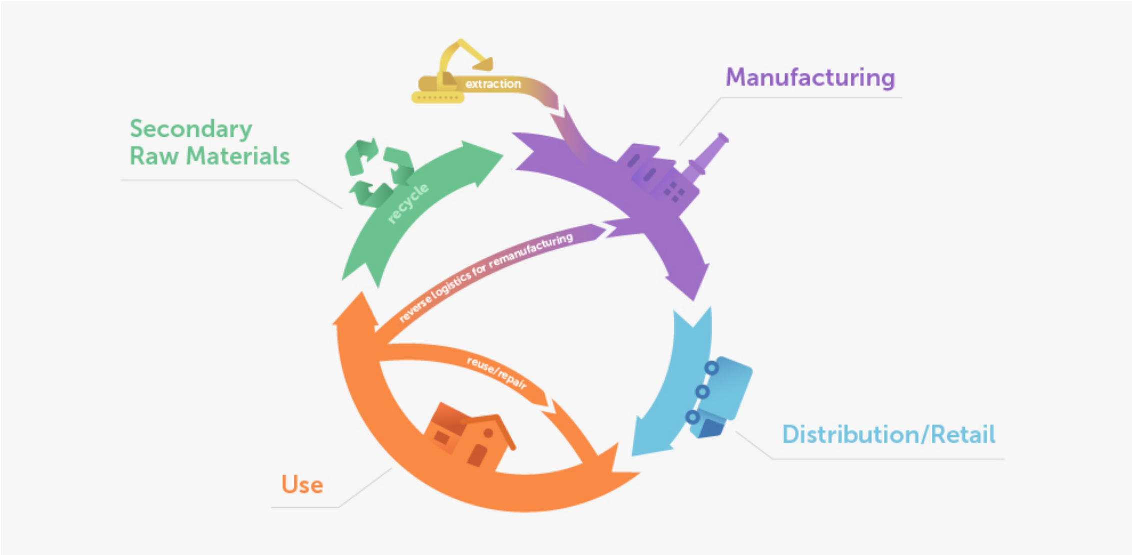

Figure 7: Reuse, repair, remanufacture and recycle in the CE context, adapted from Circuleire 2023.

Moving from the traditional linear supply chain to a CE requires the implementation of new industrial strategies, such as reuse, repair, remanufacture and recycle (Jansson 2016; MacArthur et al. 2013; Bauer et al. 2020). The implementation of circular economy logic will replace production with sufficiency; reuse what you can, recycle what cannot be reused, repair what is broken, and remanufacture what cannot be repaired (Stahel 2016). Adapting circular strategies enables companies not only to act sustainably, but also to create competitive advantage (Antikainen et al. 2018). Although the concepts of repair and recycling are commonly known when discussing CE, there is a lack of consensus in the literature regarding the definition of reuse. As a result, a brief explanation of each term is provided below. Figure 7 provides a visual representation of the four strategies within the context of the CE. To gain a better understanding of the application of these strategies in the maritime supply chain, refer to Figure 8.

Reuse

The reuse strategy is defined as "any operation in which products or components that are not waste are used again for the same purpose for which they were conceived" (Commission 2020b). One can argue that remanufacturing and repair are strategies which also can be defined as reuse, therefore this thesis will differentiate reuse by specifying reuse as "directly reuse" which includes products and components reused by another customer and where the process only requires light cleaning and testing (Bauer et al. 2020). One way of direct reuse Milios et al. 2019 highlights is the reuse of ships for the same function. Ships and their components may be purchased by new owners and placed into similar kinds of services. From now, the term "reuse" will be used to refer to "direct reuse".

Repair

Repair is defined as the repair and maintenance of a defective product which is still in good condition and fulfils its original function (Potting et al. 2017). Repair and maintenance of vessels are extensively used in the maritime industry and make up for significant operating costs (Milios et al. 2019). Ship maintenance and repair services including overhauls, servicing programs, and damage repairs of ships and their equipment. These can both be unplanned, such as in the case of unexpected system failure, or planned, such as periodical or condition-based servicing. To minimise the time that ships are out of service, maintenance and repair jobs are often carried out under severe time constraints, thus requiring the work to be completed as quickly as possible (Shipbuilding (WP6) 2010).

Recycling

Recycling plays a pivotal role in transitioning towards a CE. We define recycling as the process of returning the raw materials or secondary materials of a product to the economy (Reichel et al. 2016). At the end of their life ships are dismantled for disposal or recycling. This approach is particularly significant in the maritime industry because of the high value of materials used in maritime products. By some estimates, 95% of ships can be scrapped and recycled (Hossain, Islam et al. 2006), with arguably the large quantity of high-quality steel being the most important resource (Shipbuilding (WP6) 2010). The recycling process is extensive as nearly every part of a ship's hull machinery, equipment, fittings and even furniture can be recycled (Mikelis 2006). The primary locations for ship recycling include Bangladesh, India, China, Pakistan, and Myanmar; with Bangladesh holding the largest share (Shipbuilding (WP6) 2010).

Remanufacture

Remanufacturing is a key strategy within the CE (Jansson 2016). Remanufacturing is the process of taking a used or end-of-life product, disassembling it, cleaning it, repairing any damaged parts, testing it, and reassembling the components of a part or product in order to return it to "as-new" condition (N. Nasr and Thurston 2006; Milios et al. 2019; Jansson 2016; Sundin 2004). The process can also involve upgrading the technology or components of the product to meet current standards or regulations.

Remanufacturing is considered a more efficient approach to material circulation compared to recycling, as it preserves a greater amount of the energy initially invested in the production process (N. Nasr and Thurston 2006). Similarly, component reuse can lead to reduced material and energy consumption compared to remanufacturing (N. Nasr and Thurston 2006). However, the feasibility of component reuse relies on the components retaining their value and conforming to the necessary standards, without compromising the durability and reliability of the final product.

Traditionally, remanufacturing also referred to as rebuild, remould, or rewound, has been a practice that has been industry-specific and involves durable assemblies (Morseletto 2020). Today the use of remanufacturing in the maritime industry is heavily defined by new owners purchasing ships and placing the product into new kinds of service by replacing old equipment and prompting retrofitting (Milios et al. 2019). In other industries, such as the automobile industry, components such as starters, alternators, and water pumps are routinely remanufactured at the end of their useful lives and returned to service (N. Nasr and Thurston 2006). More about how the maritime industry has integrated such practices will be presented in section 2.3.3.

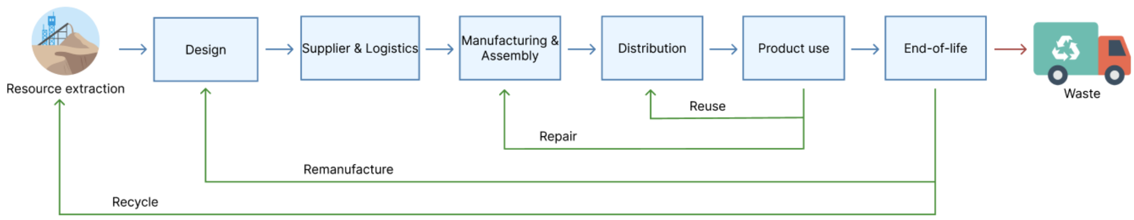

Figure 8: The four CE strategies in the maritime supply chain context, based on Jansson 2016 and Jo Wessel Strandhagen et al. 2022.

2.3.3 Remanufacturing in the maritime industry today

According to Daniel and S. Lee 2022, a substantial portion of the world's fleet has reached the end of its operational lifespan, necessitating replacement and recycling. Additionally, many mid-life vessels will need to undergo remanufacturing to meet newly implemented environmental and technological standards (Daniel and S. Lee 2022). The manner in which the maritime industry manages the EOL phase is crucial in determining its ability to transition towards a CE (Jansson 2016).

Remanufacturing has been recognized as a suitable practice for the automotive and aviation industries due to their products' high value at the end of their useful life, longer life cycles exceeding five years, and distribution through business-to-business channels (Lacy et al. 2015). In addition, according to CE principles are strategies such as remanufacturing favourable to prolong the lifetime of marine equipment and delay the inevitable stage of recycling, thus contributing to significant material resources savings and value savings in the form of labour and energy (Milios et al. 2019). Despite the compatibility of these criteria with the maritime sector, it has been considerably disregarded in discussions regarding product life extension operations (Ali et al. 2015). 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 (Milios et al. 2019; Parker et al. 2015).

One reason for the low level of remanufacturing can be blamed on the characteristics of ships and their supply chains. Remanufacturing is met with several challenges related to the infrastructure and reverse supply chains that are required to make the process financially feasible (Jansson 2016; Ali et al. 2015; Jo Wessel Strandhagen et al. 2022). Furthermore, the complex and customized nature of ship components and products poses challenges in integrating practices for remanufacturing and other circular strategies (Jansson 2016; Milios et al. 2019; Jo Wessel Strandhagen et al. 2022).

The maritime industry is lacking in transparency about what happens to the products and components removed from the vessels (Milios et al. 2019). EOL practices today commonly resort to extensive recycling for vessels that fail to meet regulatory and client requirements (Jansson 2016). Although, this practice primarily applies to the vessel's body, mechanical components, electrical and electronic parts, and other parts possess the capabilities of being utilised in the same or alternative applications, maintaining their full functionality, without resorting to recycling (Milios et al. 2019; Allwood et al. 2011).

In the maritime sector, remanufacturing, repair and reuse are critical practices that can significantly contribute to material and value savings by prolonging the lifetime of equipment and delaying the recycling stage (Milios et al. 2019). Through these activities, the economic value that would typically be lost in the traditional linear system can be retained and recaptured (Linder and Williander 2017). As these activities do not involve producing new products, they require minimal energy, virgin material, and other production inputs, further reducing their environmental impact by enabling the remanufacturing of components for replacement purposes. Therefore, it is crucial to identify opportunities for remanufacturing of maritime products and components to increase resource efficiency (Milios et al. 2019). By engaging in product life extension activities, companies can reduce their environmental impact and promote sustainable development (Jansson 2016; Wahab et al. 2018).

2.3.4 Factors that determine the potential for remanufacturing

In order to understand the determining factors for remanufacturing, we delve into relevant literature to gain insights into the various influential elements that need to be taken into account. This exploration allows us to comprehend the wide range of factors that play a significant role in the remanufacturing process.

The purpose of this section is to provide an overview of the factors discussed in the literature that have a significant impact on determining the potential for remanufacturing. These insights will be compared to the findings obtained from the comprehensive list generated during the case study, allowing for a thorough examination and comparison in the discussion section of this thesis.

In a study conducted by Ziout et al. 2014, a holistic examination of these factors was undertaken to identify the most optimal circular strategies. The authors compiled an extensive list of factors categorized into four main perspectives: engineering, environmental, societal, and business. The engineering perspective encompassed technical aspects related to products and processes, while the environmental perspective focused on resource conservation and pollution prevention. The societal perspective and business perspective accounted for factors pertaining to specific target segments, broader societal concerns, market dynamics, supply and demand, as well as political and legal considerations (Ziout et al. 2014). Although not all perspectives mentioned fall within the scope of this thesis there are multiple product factors that remain relevant for this thesis, such as the item's useful lifetime, if its standard or interchangeable components, designed for disassembly, and the value of a used product compared to a new one.

N. Nasr and Thurston 2006 explored the product delivery model, where companies produce products which are sold to the customer, are used and serviced, and then retired (through recycling, remanufacturing, or disposal). N. Nasr and Thurston 2006 found that in many cases, the product manufacturer has no role in the product life cycle, beyond the warranty period, after the product is sold to the customer. The article's four factors that determine EOL options such as remanufacture for each model, component, etc. should be evaluated after the following criteria:

- Value and cost of the component
- Technical feasibility of remanufacturing
    - can the condition be assessed for reuse,

  - can the component be extracted without damage
  - is there a known process for restoration to like-new

- Economic feasibility of remanufacturing

  - Recoverable value at end-of-life
  - Cost to extract from a product and cost to convert to like-new

- Disposal options and environmental impact or legislation

Lund and Hauser 2010 presents six criteria for successful product remanufacturing, drawing on 25 years of research in the remanufacturing industry (Charter and Gray 2008). The first three criteria focus on the technological aspect of remanufacturing: 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 savings (Lund and Hauser 2010). The fourth criterion stresses the importance of stable product technology over multiple life cycles to ensure quality and performance (Lund and Hauser 2010). The fifth criterion emphasizes sufficient market demand for remanufactured products, providing economic incentives for businesses to engage in remanufacturing activities (Lund and Hauser 2010). Lastly, evaluating disposal options and considering the environmental impacts of legislation is crucial in determining a product's suitability for remanufacture (Lund and Hauser 2010; Charter and Gray 2008).

According to an article by Russell and N. Z. Nasr 2023, not all circular strategies are suitable for every product. The study quantitatively demonstrates that all circular strategies outperform newly manufactured products in terms of environmental impact, material consumption, and economics. They emphasize that product characteristics and design are crucial in determining the feasibility and potential of implementing circular strategies (Russell and N. Z. Nasr 2023).

Lastly, Sundin 2004 identified nine preferable product properties that would fit remanufacturing process. Here the remanufacturing process includes inspection, cleaning, disassembly, storage, reprocessing, reassembly and testing (Sundin 2004). The nine properties are wear resistance and ease of identification, verification, access, handling, separation, securing, alignment, and stacking. Sundin 2004 concluded, based on multiple case studies, that ease of access, ease of identification, wear resistance, and ease of handling as the most frequently important properties.

After conducting research on the topic, a table of product factors has been created, see Table 5. The relevant aspects are product performance, innovation rate, design, technical specification, damage, location of product/component, remanufacturing process and economics.

Table 3: Product factors determining the potential for remanufacturing based on literature.

Product factors	**Description**	**Reference**
Product performance	Product performance is the same as new product. (Quality, efficiency, ...)	[1], [2]
	Quality	[2]
Innovation rate	Market technology change rate	[2], [3]
	Product technology is stable over more than one life cycle	[2], [3]
Design for remanufacturing	Design for disassembly	[1], [2], [4], [5]
	Standards components	[1], [2], [3], [4], [5]
Technical specification	Disposal options	[1], [2], [3]
	Material value	[2], [5]
	Product documentation	[4]
	Technical lifetime	[2]
	Regulations	[1]
Level of damage	Degree of rust, corrosion, etc.	[4]
Location of product	Product/component location	[2]
	Geographical location	[2]
Process	Established reverse logistics	[1], [2], [4], [5]
Economic	Cost of remanufacturing process	[2], [5]
	Economic load of new product vs. used product	[1], [2], [5]
[1]: N. Nasr and Thurston 2006 [2]: Ziout et al. 2014 [3]: Sundin 2004 [4]: Charter and Gray 2008 [5]: Russell and N. Z. Nasr 2023		

2.4 Digital technologies

The term "digital technologies" has been used as the basis of this thesis, building on the foundational concept of Industry 4.0 (I4.0) (Kagermann et al. 2013; Kristoffersen et al. 2020).

I4.0 is defined as the fourth industrial revolution, characterized by the integration of advanced DTs into the manufacturing process (Aldrighetti et al. 2022). I4.0 has enabled manufacturers to improve their production processes and respond more quickly to changing market demands (Aldrighetti et al. 2022; Sousa Jabbour et al. 2018; Jo Wessel Strandhagen et al. 2022). The application of I4.0 enables real-time monitoring and controlling of important production parameters such as production status, energy consumption, the flow of materials, customer orders, and suppliers' data (Sousa Jabbour et al. 2018). As a result, organizations can develop products that meet real customers' needs due to the connectivity and communication these advanced technologies facilitate (Sousa Jabbour et al. 2018).

I4.0 technologies emerge as promising means for managing the complexity of an ETO environment (J. Strandhagen et al. 2019). While research has shown that the application of I4.0 technologies can significantly improve the performance of a supply chain (POR 2014-2020; Aldrighetti et al. 2022; Dalenogare et al. 2018), the practical use of I4.0 has not been sufficiently compared to other more repetitive manufacturing (Jo Wessel Strandhagen et al. 2022). The need for coordination of material and information flows in ETO supply chains is significant (Mello, Gosling et al. 2017; J. Strandhagen et al. 2019), and tailored approaches are required for effective and efficient management of manufacturing operations (Adrodegari et al. 2015).

Industry 5.0 (I5.0) on the other hand is a new development in the field of advanced manufacturing that builds upon the concept of I4.0. It is characterized by the integration of advanced DTs with human creativity, skills, and knowledge (Xu et al. 2021). This approach aims to create a more sustainable and equitable manufacturing ecosystem through collaboration between human workers and intelligent machines. I5.0 emphasizes the human experience in manufacturing, including the use of advanced technologies to enhance worker safety, well-being, and job satisfaction (Xu et al. 2021). While I5.0 represents an important evolution in the field of manufacturing, it is important to note that it goes beyond the scope of this thesis. By focusing on DTs, the thesis seeks to provide insights into how manufacturers can leverage these tools to ease the implementation of remanufacturing in their supply chains.

Although DTs are a frequently discussed concept in manufacturing research, there is no clear consensus in the literature about which types of technologies it includes (Sousa Jabbour et al. 2018). To determine which technologies to cover in this thesis, the structural overview for complex ETO companies provided by J. Strandhagen et al. 2019 is used as a basis, see Table 18. The table is further developed by including technology presented by

Sousa Jabbour et al. 2018 literature on the CE and I4.0 technology, Rüßmann et al. 2015 nine technologies transforming industrial production, and Zheng et al. 2021 technologies in a manufacturing context. Additionally, recommendations from emerging technologies in remanufacturing presented by Kerin and Pham 2019 are included to keep the technologies within the application area of remanufacturing.

Table 4: Overview and description of digital technologies for remanufacturing in an ETO environment.

No.	**Tech.group**	**References**
1	Automation and industrial robots	[1], [2], [3], [6], [7]
2	Additive manufacturing	[1], [2], [3], [4], [6], [7]
3	Cyber-physical systems (CPS)	[1], [5]
4	Data analytics	[1], [2], [3], [4], [5], [6], [7]
5	Integration of IT systems	[2], [3]
6	Internet of Things (IoT)	[1], [2], [3], [4], [5], [6], [7]
7	Visual technology	[1], [2], [3], [4], [6], [7]
8	Simulation and modelling	[1], [3], [6], [7]
9	Cloud Technology	[1], [2], [3], [5], [7]
10	Blockchain	[1], [6]

[1]: Zheng et al. 2021
[2]: J. Strandhagen et al. 2019
[3]: Rüßmann et al. 2015
[4] Jo Wessel Strandhagen et al. 2022
[5]: Sousa Jabbour et al. 2018
[6]: Kerin and Pham 2019
[7]: Sullivan et al. 2020

Automation and industrial robots

Automation technologies, such as robotic process automation (RPA) and artificial intelligence (AI), can be used to streamline production processes, reduce labour costs, and improve quality control (Zheng et al. 2021; Jo Wessel Strandhagen et al. 2022). By automating manual repetitive and dangerous tasks, manufacturers can free up their employees to focus on more complex and strategic activities (Zheng et al. 2021; Jo Wessel Strandhagen et al. 2022). Automation can also improve quality control by reducing the risk of human error and ensuring consistent output.

Additive manufacturing

Additive manufacturing, also known as 3D printing, is a process of creating three-dimensional objects by building objects layer-by-layer from a digital design file such as CAD (J. Strandhagen et al. 2019). Additive manufacturing enables the production of customized products with a high degree of precision and accuracy, reducing waste and increasing efficiency (Sousa Jabbour et al. 2018).

Cyber-physical systems

Cyber-physical systems (CPS) refer to the integration of physical components with computational and networking capabilities, allowing them to sense their environment, process information, and interact with other systems in real-time (Zheng et al. 2021; Sousa Jabbour et al. 2018). This technology has a wide range of applications in manufacturing, including predictive maintenance, quality control, and production scheduling. With CPS, manufacturers can predict when maintenance is needed, monitor production processes in real-time, and optimize operations by predicting demand and managing resources (Zheng et al. 2021). This is made possible through the use of sensors and actuators that gather and distribute real-time data for decision-making purposes (Sousa Jabbour et al. 2018).

Data analytics

Big data and analytics, transform data into knowledge and action within a manufacturing system (J. Strandhagen et al. 2019). Big data analytics involves the collection, processing and analysis of large and complex data sets (Zheng et al. 2021). In the context of manufacturing, big data analytics can optimize production processes, improve quality control, and enhance supply chain management by processing data in higher volumes, with higher velocities, and greater variety (Zheng et al. 2021). An example, big data analytics can improve quality control by recognizing patterns and trends that may indicate quality issues (Rüßmann et al. 2015).

Integration of IT systems

Horizontal and vertical integration of IT systems for production management (PLM, ERP, MES) (J. Strandhagen et al. 2019). Horizontal and vertical integration of IT systems can mean that companies, departments, functions, and capabilities will become much more cohesive, as cross-company, universal data-integration networks evolve and enable truly automated value chains (Rüßmann et al. 2015).

Internet of Things

IoT refers to the network of physical devices and appliances embedded with electronics, software, sensors, and connectivity, enabling them to connect and exchange data (J. Strandhagen et al. 2019; Zheng et al. 2021; Sousa Jabbour et al. 2018). IoT can be used in manufacturing for real-time monitoring, predictive maintenance, and supply chain management. Real-time monitoring of production processes is a key application of IoT in manufacturing (Zheng et al. 2021). This involves collecting and analyzing data from sensors on machines to identify potential problems before they cause downtime or quality issues (Zheng et al. 2021), which is also called predictive maintenance. Additionally, IoT can be used in supply chain management to enable manufacturers to track inventory and logistics, improving efficiency. The most common resources used in implementing the IoT are Radio Frequency Identification (RFID) technology tags, sensors, barcodes, and smartphones (Sousa Jabbour et al. 2018; Da Xu et al. 2014).

Visual technology

Technology to construct a visual representation of an object, in the form of augmented reality (AR), through computer-generated 3D images in the real world, creating a virtual reality (VR) or projecting 3D images as holograms (J. Strandhagen et al. 2019). One key application of AR in manufacturing is maintenance, by overlaying computer-generated information on top of physical equipment, technicians can quickly identify issues and make repairs (Zheng et al. 2021). AR can also be used for training, by providing trainees with virtual simulations of equipment and processes.

Simulation and modelling

Simulation and modelling technologies can be utilized to enhance production processes, quality control, and reduce wastage (Zheng et al. 2021). Real-time data can be leveraged to create virtual models of the physical world, including machines, products, and humans, which allows operators to optimize machine settings for the next product in line before the physical changeover, resulting in reduced machine setup times and improved quality (Rüßmann et al. 2015). Manufacturers can enhance their operations and boost overall efficiency while minimizing errors and downtime by utilizing virtual models of manufacturing processes (Zheng et al. 2021). This enables operators to experiment and enhance machine settings for the subsequent product in the virtual domain prior to the physical changeover, ultimately leading to reduced machine setup times and enhanced quality (Rüßmann et al. 2015).

Cloud Technology

Cloud technologies are systems for the provision of online storage services for all applications, programs and data in a virtual server, without required installation (Zheng et al.

2021). In manufacturing, cloud manufacturing is a technology that utilizes the internet to establish a virtual and worldwide platform for manufacturing resources and abilities. It operates on a service-based concept, which implies that customers and suppliers work together to offer and purchase various services like designing, simulating, manufacturing and assembling products (Rüßmann et al. 2015; Sousa Jabbour et al. 2018).

Blockchain

The utilization of blockchain technology can enhance supply chain management by offering a secure, transparent, and decentralized method to trace goods and transactions (Zheng et al. 2021). With the help of blockchain, producers can monitor the progress of goods from their initial raw materials to the final product, and ensure that all participants in the supply chain are responsible for their actions.

2.4.1 Barriers to the implementation of digital technologies

The rapid evolution of DTs has led to significant transformations across various industries, with particular attention focused on production and logistics within the realm of digital advancements. The integration of these technologies holds the promise of numerous benefits, such as enhanced product customization, improved product quality, cost reduction, increased productivity, shortened product launch cycles, sustainability improvements, enhanced process visualization and control, and heightened worker satisfaction (Dalenogare et al. 2018, Jo Wessel Strandhagen 2022).

However, despite these enticing prospects, numerous barriers hinder companies from effectively implementing digital technologies. These barriers encompass various aspects, including governmental regulations, financial constraints, technological complexities, organizational challenges, and human resource-related factors (Da Silva et al. 2020, Glass et al. 2018, and Raj et al. 2020). To shed light on these barriers, prior research conducted by Da Silva et al. 2020; Glass et al. 2018; Raj et al. 2020 is utilized together with the work of Jo Wessel Strandhagen 2022 to present a table illustrating potential barriers to the implementation of I4.0 technologies, see Table 5.

Table 5: Barriers to the implementation of digital technologies in manufacturing (Jo Wessel Strandhagen 2022).

Barriers	**Description**
High investment cost	Implementation of digital technologies may require significant capital investments, which may pose a challenge for companies
Lack of clarity or understanding of the economic benefits	Without a clear understanding and proof of the economic benefits of technology applications, companies may be reluctant to invest in implementation
Challenges in or lack of supply chain integration and collaboration	The realization of certain potential benefits of I4.0 technologies requires close collaboration and tighter integration across supply chain actors, which may be both challenging and undesirable.
Low maturity level of technologies	While the technological developments may have come far, their industrial application may still be at a low level of maturity, or technology readiness level (TRL). this may cause reluctance to implement them
Lack of standards, governmental regulations, and policies.	The implementation of rapidly developing advanced technologies may be hindered by a lack of associated standards, regulations, and policies, which are developing at a slower pace.
Inadequate technological infrastructure	The advanced technologies of I4.0 requires a certain level of technological infrastructure to be applicable in the industrial context. Accordingly, inadequate technological infrastructure may prevent technology implementation
Lack of human resources and digital skills.	A lack of knowledge and skills among employees regarding the use of digital technologies, and a lack of human resources dedicated to digitalization-related activities, may impede companies' ability to use the desired technologies.
Internal resistance to change	Resistance or unwillingness of employees to change their way of working or working methods may be a barrier to implementation, as new digital technologies may disrupt or require changes in traditional practices.
Ineffective change management	The transition to I4.0 technology application may be complex and challenging and may require highly effective change management
Lack of, or difficulties in forming, a digitalization strategy	A comprehensive implementation of and transition to I4.0 technologies can require significant changes to a company's operations. Accordingly, a strategy for digitalization may be necessary.

2.4.2 How digital technologies can impact the maritime industry

DTshave a significant potential to improve industrial performance (Dalenogare et al. 2018). As previously mentioned in the introduction to this thesis, the maritime industry is lagging behind other industries in manufacturing regarding digitalization (Jo Wessel Strandhagen et al. 2022). According to the Maritime21 report, "digitalization in the maritime industry is about using technology to ensure efficient operations, reduce costs, enhance safety and create new services and markets" (Mellbye, Rialland et al. 2016).

This section, explores the technologies identified in the literature from Section 2.4. By examining these technologies, we will clarify how various technologies can impact and benefit the maritime sector. Additionally, these insights, combined with other research findings on DTs, will contribute to a comprehensive understanding of how these technological advancements can facilitate the integration of remanufacturing practices within the maritime industry.

Automation and industrial robots

Robotics, automation and remote control are closely linked (Mellbye, Rialland et al. 2016). The use of robotics and automated production are promising areas, offering to improve the quality and reliability of maritime products (Sullivan et al. 2020). This includes the use of autonomous vessels, and drones for inspections, cargo handling, automation, robotic maintenance and repairs, and unmanned underwater vehicles for subsea exploration (Shenoi et al. 2015). The use of this type of technology can reduce human risks, and increase safety and reliability (Mellbye, Theie et al. 2015).

Additive manufacturing

Research into the viability of additive manufacturing for maritime has been ongoing for over 25 years and indicates that this technology holds significant potential for substantial cost reductions in shipbuilding and maintenance processes (Sullivan et al. 2020). The utilization of additive manufacturing technology offers significant advantages in terms of financial risk reduction during prototype development and decreased costs associated with spare parts production (Mellbye, Rialland et al. 2016). Additionally, additive manufacturing will provide greater design freedom (Shenoi et al. 2015, which can minimize transportation within the production chain and enable short production cycles (Sullivan et al. 2020).

Cyber-physical systems

CPS systems can be used in the maritime industry to monitor ship performance in real-time and carry out environmental monitoring (Mellbye, Rialland et al. 2016). The "Global Marine Technology Trends 2030" report by Lloyd's Register highlights the increasing connectivity and integration of systems onboard vessels, leading to the emergence of smart and connected ships. These ships utilize CPS technology to enable seamless communication between various onboard systems, sensors, and devices (Shenoi et al. 2015). Other potential benefits maritime products can get from CPS are enhancing vessel performance, safety, and operational efficiency (Shenoi et al. 2015).

Data Analytics

Big Data analytics tools make it possible to analyze these large quantities of data use of sensors and real-time monitoring brings in order to gain insight that supports decision-making, improve operational efficiency, and risk assessment (Mirović et al. 2018; Shenoi et al. 2015). Ship performance and navigation information can be used to develop navigation strategies to improve ship energy efficiency by monitoring fuel consumption, various emissions, the use of lighting, heating and similar processes (Mirović et al. 2018).

Integration of IT systems

By integrating sensor technology and implementing systematic data management, efficiency can be significantly improved throughout the transport and logistics value chain (Mellbye, Rialland et al. 2016). This includes various stakeholders such as shipping companies, service providers, ports, authorities, and classification companies (Mellbye, Rialland et al. 2016). Moreover, the growing integration of ship design, construction, and operation through collaborative platforms involving multiple disciplines enables faster and more cost-effective development processes (Mellbye, Rialland et al. 2016).

In order to adapt to the rapid integration of new technologies into interconnected systems, it becomes essential to establish a software and electronics environment that is both flexible and secure (Shenoi et al. 2015). This adaptation will ensure the seamless integration of emerging technologies into existing systems and systems of systems (Shenoi et al. 2015).

Internet of things

Another technology that is becoming increasingly important for the maritime industry is the IoT (Mellbye, Rialland et al. 2016). IoT plays an important role in collecting and transmitting real-time data from various sensors and devices. It enables remote monitoring, condition-based maintenance, asset tracking, and optimization of vessel performance and energy efficiency (Shenoi et al. 2015). Additionally, IoT technology holds immense potential for optimizing planning, proactive incident management, and operational predictability (Mellbye, Rialland et al. 2016).

Visual Technology

AR and VR technologies possess the potential to revolutionize the maritime industry by transforming training, facilitating remote inspections and other collaborations, and maintaining operations (Shenoi et al. 2015).

The utilization of CAD/CAE (Computer-Aided-Design/Computer-Aided-Engineering) has long been established in vessel development, enhancing various stages of the design process to ensure shorter lead times (Sullivan et al. 2020). In the current digitally-driven environment and with the increasing complexity of system integration, the production, and operation of CAD/CAE tools and AR become more crucial than ever (Sullivan, 2020). They support individuals involved in the construction process by enabling tasks such as assembly, context awareness, and data visualization (Sullivan et al. 2020). By combining VR applications with traditional design tools like CAD, it becomes possible to design and allocate onboard equipment while identifying any deviations between a CAD model and the corresponding assembly part (Shenoi et al. 2015).

Cloud Technology

Cloud computing applications for product data will enable the effective use of resources internationally and will contribute to greater product mobility, thereby overcoming short-term localisation constraints (Shenoi et al. 2015). The adoption of cloud computing technology will provide reliable information and immediate processing for all actors of a supply chain making a collaborative environment offering cross-border e-maritime services (Dellios and Papanikas 2014).

Blockchain

Pu and Lam 2021 presented key features of blockchain technology that hold great relevance for utilization in the maritime industry. The article states potential by leveraging its distributed nature, immutability, peer-to-peer transmission, time-series data tracking, visibility, anonymity, and smart contract capabilities. These features can enhance information sharing, improve efficiency, reduce costs, and increase transparency and trust among stakeholders, ultimately driving innovation and transforming various aspects of the maritime sector (Pu and Lam 2021).

2.4.3 How digital technologies can enable the circular economy

Digitalisation's role as an important enabler of the CE is widely accepted (Antikainen et al. 2018; Kristoffersen et al. 2020; Jabbour et al. 2019). Here, digitalisation refers to DTs that are currently transforming the industry (Antikainen et al. 2018). In the following paragraphs of this section, you will be presented with a few application areas and remarks on how they can provide CE benefits.

One of the most significant benefits of DT in the CE is the increased visibility and intelligence into products and assets and products. The increasing use of DTs such as AI and blockchain technology brings novel ways to improve traceability and transparency throughout product lifetime (Antikainen et al. 2018; Stankovic et al. 2017). This includes knowledge of the location, condition, and availability of assets and products (Antikainen et al. 2018).

The real-time knowledge of the product location is critical in enabling increased product accessibility and improves the possibilities for end-of-life collection, refurbishment, remanufacturing, and recycling (Bressanelli et al. 2018). For instance, the IoT can enable automated location tracking and monitoring of natural capital (Kristoffersen et al. 2020; MacArthur and Waughray 2016). Technologies such as RFID help to collect information about how the product has been used, which plays a central role in understanding how we can monitor product history. This data can be used to estimate the quality of returned products and facilitate the return flows into product life cycle management (Antikainen et al. 2018; Pagoropoulos et al. 2017).

In a CE, coordination of material and information flow is crucial (Antikainen et al. 2018). Information about the quantity and quality of products and their raw materials contents needs to be collected and retained (Antikainen et al. 2018). The IoT is one of the most significant DTs that can be employed to achieve this. With the help of innovative applications, IoT can present a common operating picture. This is possible with seamless large-scale sensing, data analytics, and information representation using cutting-edge ubiquitous sensing and cloud computing (Gubbi et al. 2013). With the use of IoT, remanufacturers will be able to analyse used products and link the physical conditions of the assets with sensor data, and ultimately able to interpret usage data to reach more accurate remanufacturing decisions, which will improve the efficiency of remanufacturing operations (Okumus et al. 2023).

A digital twin is another method for defining and modelling a physical item's properties, characteristics, components, and performance using advanced digital tools (Okumus et al. 2023; 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 equivalent (Okumus et al. 2023; Tozanlı et al. 2020). Once invested in equipment and IoT sensors, one can monitor consumption levels, run cycles and malfunctions during the product's lifetime and provide precise data on the products' behaviour at the product and component level through the use of digital twin technology (Tozanlı et al. 2020). Additionally, digital twin models include all relevant product information, including serial numbers, model names, production dates, bills of materials, and assembly/disassembly instructions (Alqahtani et al. 2019).

To summarise, digitalisation plays a vital role in enabling the circular economy by providing increased visibility, traceability, and intelligence into products and assets. DTs such as AI, blockchain, and the IoT offer novel ways to improve transparency, product accessibility, and EOL processes. These technologies facilitate real-time knowledge of product location, automate tracking and monitoring, and collect valuable data on product history and usage. The coordination of material and information flow is crucial in the CE, and IoT can be employed to achieve seamless sensing, data analytics, and information representation. Furthermore, digital twin technology allows for the precise modelling and monitoring of physical items, enabling accurate data on product behaviour and comprehensive product information. Overall, digitalisation contributes significantly to the implementation and success of the CE. So far, the answers to questions such as in what areas and in which ways, DTs support for implementing circular strategies for manufacturing have been insufficiently systematized (Kerin and Pham 2019). The discussion chapter of this thesis aims to make a valuable contribution towards identifying the uncertainties that can be mitigated through the application of DTs in remanufacturing.

3 Methodology

This section presents the methods and tactics employed to answer the research questions and objectives of the thesis. This section is crucial as it allows the reader to assess the validity and reliability of the study by understanding how the data was collected, analyzed, and interpreted.

According to Kothari 1993, the methodology is a structured and theoretical analysis of applicable methods that can be used in a specific field of study to find solutions to research problems. Although the terms "methodology" and "methods" are often used interchangeably, Greener 2008 points out that methodology is a comprehensive understanding of applied methods, while methods refer to specific techniques used for a given task. Research methods refer to the techniques used to gather data and information (Karlsson 2010). Research methodology often involves different research methods. This chapter aims to discuss the methodological aspects of the research.

3.1 Research methods

Research methods are described as either quantitative or qualitative (Karlsson 2010). Quantitative research deals with a wide range of situations, where specific results or data are presented. This data can be based on numerical methods, mathematical models or laboratory experiments (Greener 2008). It often involves large sample sizes and controlled experiments produce empirical evidence. Qualitative research is exploratory and subjective, aiming to understand complex social phenomena by analyzing and interpreting non-numerical data such as text, images, and observations. Qualitative research typically involves smaller sample sizes and relies on methods such as interviews, focus groups, and case studies to gather data (Greener 2008).

According to Karlsson 2010 there are three approaches to building a logical argument, namely deduction, induction and abduction. All three are built on the same three components: rule, observation and result. The rule is about how the world is structured and functions. A second component is a condition that has been empirically observed: the database or the research material. The third component is the result or conclusion. The three ways of arguing differ on where they take their starting point and how then the logic goes on (Karlsson 2010; Greener 2008). How the components are combined into the different approaches can be seen in Figure 9. This thesis uses an inductive approach, meaning that the argument starts with something observed empirically, trying conclusions to find the rule (Karlsson 2010). The qualitative approach is associated with the inductive approach to generate theory, due to the use of interpretive models that allow for multiple subjective perspectives and constructing knowledge rather than seeking to find it in reality (Greener 2008).

Approach					
Deductive	Rule	→	Observation	→	Result
Inductive	Observation	→	Result	→	Rule
Abductive	Result	→	Rule	→	Observation

Figure 9: Different logical approach to argumentation, based on Karlsson 2010.

3.2 Mixed-methods research

This master's thesis utilized a mixed-methods approach, incorporating both a quantitative research method and a qualitative research method. Both approaches have their strength and limitations but can be used in combination to gain a more comprehensive understanding of a research question (Greener 2008). The research drew on information from multiple sources, including interviews, formal discussions, literature study and the preliminary literature study conducted during the specialization project. As there is minimal research on the scope of interest, the focus has not been on confirming the existing theory, but rather to discover important features not previously studied in the literature. Therefore, the research of this thesis is closer to an inductive approach than a deductive one (Karlsson 2010). The following subsections will present the implementation and utilization of the methods.

3.3 Literature study

A fundamental part of any academic research is reviewing existing literature, establishing the legitimacy and authority of the research, and understanding the scope of the research (Croom 2010). To provide a foundation for knowledge on the ETO environment, maritime industry, CE and DTs a literature study was performed. The literature study was focused on answering the research questions and used to establish a theoretical base for meeting the research objectives and identifying research gaps.

Initial searches were conducted to explore the field and identify keywords relevant for the next stage of the literature study, keyword searching. Due to the limited number of results, when searching for all three keyword blocks, a concept-related block and two context-related blocks were created for a sufficient result. The first block contains the CE term to analyze, namely circular strategies and remanufacturing. The second concept-related block holds the DTs and the I4.0 paradigm. Lastly, the third and third concept-related blocks include the ETO environment and the maritime industry. The concept and two context-related groups were connected with the "AND"-operator, and the keywords variations within the group were connected with a Boolean operator "OR".

To facilitate searching for relevant papers, the keywords were identified; see Table 6. The material collection was gathered from Scopus, Google Scholar and Web of Science. The search was constrained only to identify papers that contained specific keywords in their abstracts, titles or the list of papers list of keywords. This includes scientific journals, book sections, conference proceedings and company papers. Then, the results of the papers were exported to EndNote Library, where automated removal of duplicates was performed. The remaining papers were exported to an Excel sheet to be organized on the title, authors, and year published and manually screened for duplicates that were not filtered in the previous automated removal.

Table 6: Defined keywords for literature search

Keywords			
Concept-related block	“circular supply chain” OR “closed loop supply chain” OR “prolonging product life cycle” OR “product life cycle” OR “end of product life” OR “circular economy” OR “circularity” OR “circular supply chain” OR “ closed loop supply chain” OR “closed supply chain” OR “closed loop” OR “open loop supply chain” OR “loop supply chain” OR “closed value chain” OR “closed loop value chain” OR “sustainability” OR “sustainable” OR “self-sufficient” OR “self sufficient” OR “three pillars of sustainability” OR “3 pillars of sustainability” OR “ reverse logistic” OR “remanufacturing” OR “re manufacturing” OR “reuse” OR “reusing”OR “remanufacture” OR “recycling” OR “recycle”		
AND			
Context-related block	“industry 4.0” OR “I4.0” OR “industry 5.0” OR “fourth industrial revolution” OR “smart manufacturing” OR “digitalization” OR “digitalised” OR “digitized” OR “digitise” OR “digitize” OR “technology” OR “tech” OR“smart logistics” OR “smart factories” OR “smart factory” OR “digital twin” OR “automated engineering” OR”augmented reality” OR ”virtual reality” OR ”automated robots” OR ”big data” OR ”data analysis”	**OR**	engineer-to-order” OR “ETO” OR “engineer to order” OR “engineered to order” OR “engineered-to-order” OR “eto” OR ”project manufacturing” OR”project-manufacturing” OR “production planning”OR “project-production” OR ”project-based manufacturing” OR “Project based manufacturing” OR “customized production” OR “customised production” OR “customized manufacturing” OR “customised manufacturing” OR “make to order” OR “make-to-order” OR “made to order” OR “made-to-order” OR “shipbuilding” OR “maritime supply chain” “maritime sc” OR “shipbuilding supply chain OR “shipbuilding sc”

Further, titles and abstracts were screened by following, excluding papers that did not follow the exclusion criteria:

1. Language limited to English.

2. Focusing on topics that are unrelated or vaguely related to ETO or non-repetitive manufacturing.

3. The year published.

(a) To ensure the obtainment of relevant and updated information on the topic of DTs and I4.0, an additional criterion was required to be met. The term I4.0 was first introduced in 2011, thus research published before 2011 will not consider this term and therefore less relevant to the topic of this thesis.

(b) For keywords regarding ETO and CE, this criterion was not a requirement.

4. The year the literature was published was limited to 2011-2023.

5. A full-text screening, including titles and abstracts, was performed to exclude papers that were not related to the main scope of this literature review e.g., papers not contributing to the theory in the field of supply chain management in ETO situations, CE or DTs.

The exclusion criterion further considered 152 papers and removed papers from further review. In addition to the literature study and with the motivation to further enrich the search results, an additional 24 papers were included from a snowballing strategy. Snowballing was applied based on references and authors of publications from the result of the literature study. In total, after the exclusion criterion and the additional papers included through snowballing, the result of 73 papers was read and analysed.

3.4 Case study

A case study research method has been widely used in operations management as one of the most powerful research methods (Karlsson 2010). This method is particularly useful when investigating the "how" and "why" of topics (Yin 2009). It is a research strategy that focuses on understanding the dynamics present in a setting (Tobro 2017). The process may encompass one or more cases, employing various techniques to collect data, examining different levels of analysis, and utilizing either quantitative or qualitative data that is generated through empirical means (Yin 2009; Voss 2010; Eisenhardt 1989). The choice of case study as the primary research method in this study was informed by various advantages. First and foremost, it facilitates the generation of novel theories by identifying patterns and linkages between critical variables (Voss 2010). As the research seeks to advance the knowledge of how ETO companies can establish remanufacture in their supply chain, the use of a case study is appropriate as it enables the collection of data from actual situations. The direct engagement of key employees of each company enables the answers to questions of what, why, and how, to be answered with comprehensive understanding (Tobro 2017; Benbasat et al. 1987). The subsequent paragraphs will provide valuable information regarding the process of case selection, methodologies employed for data collection, and the procedures utilized for analyzing the gathered data.

3.4.1 Case selection

As previously indicated, case research can be carried out on single or multiple cases. A single case study provides an opportunity for an in-depth examination of several contexts within the case simultaneously. However, its applicability to the generalization of conclusions is limited (Voss 2010). More about case study limitations will be presented in Section 3.6. To address the limitations associated with single case studies, a multiple case study approach was adopted to facilitate the comparison of results across several cases.

The process of case selection is significant in the development of new theories, as it determines the entities from which the research sample is to be drawn (Eisenhardt 1989). The experience gained during the specialization project highlighted the importance of considering perspectives from various stakeholders in the maritime industry, given the close relationships between large equipment suppliers, other suppliers, shipyards, shipping companies, and classification societies. This was taken into account in the selection of case study participants. To ensure the case companies selected for this study remained relevant to the research scope, a specific set of criteria was established. The companies chosen for the study met all criteria.

Firstly, the company should encompass characteristics as developed from section 2.1. For the sake of generalizing the conclusion the chosen companies should ideally represent diversity among their manufacturing activities and stakeholder position. The visual representation displayed in Figure 10 illustrates the correlation between the annual production volume of products/systems on the x-axis, and the level of customization complexity expressed as the number of engineering hours per product/system on the y-axis. In Table 7, you will find a summary of companies characteristics.

Table 7: Summary of companies characteristics

Company	**Volume (quantity per year)**	**Duration (weeks)**	**Cost per unit (thousands Euro)**	**Engineering hours (hours per unit)**
Company A	200 - 300	11 - 50	101 - 1000	101 - 1000
Company B	1 - 10	> 100	50 000	> 30 000
Company C	900	51 - 100	1000	8000
Company D	1 - 10	51 - 100	101 - 1000	1001 - 10 000
Company E	-	-	-	-
Company F	10 - 20	12 - 24	1000 - 2000	101 - 1000

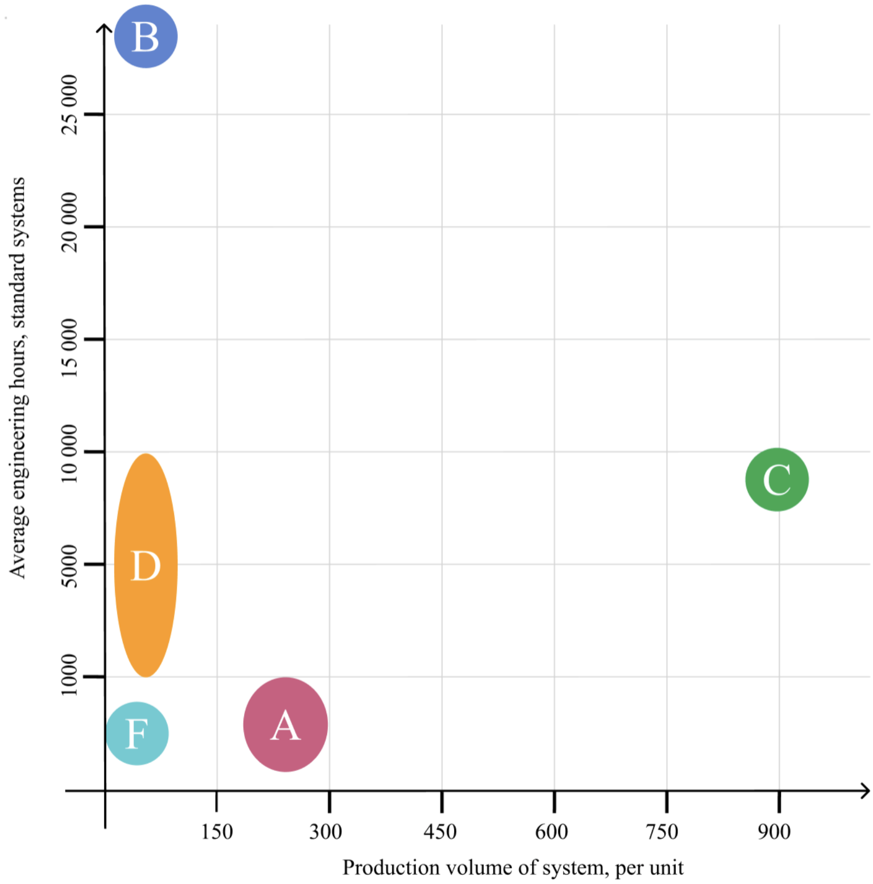

Figure 10: Product-process matrix placing companies, adapted by Tobro 2017

The second criterion is building on the previous criteria, the case company should be serving the maritime industry, and represent at least one of the five stakeholders in the maritime industry presented in Section 2.2.2. This way the answers remain relevant within the same industry and possible examples and experiences can more easily be compared.

The final criterion pertains to the aspect of CE, which requires the company to have explored CE strategies and reflected on the potential implementation of sustainable development in their operations. Without such exploration and understanding of remanufacturing's potential for the company, opinions and arguments would solely be based on speculation rather than experience.

It is necessary to note that the ETO companies involved in the empirical part of this thesis deliver products to the maritime industry, which imposes strict rules and legislation from governmental bodies, classification societies and independent third-party verification companies (Jünge 2022). Thus, having the perspective of such an organisation was important for the understanding of how CE strategies could be integrated. Therefore, one case company is a classification society and does not fulfil the criteria of manufacturing ETO products.

To ensure effective data collection, it is crucial that the point of contact in each case is a knowledgeable informant with an in-depth understanding of the company's operations. Ideally, the interviewee should also have a solid grasp of the relevant theoretical aspects discussed. Measures taken to ensure this will be discussed in Section 3.5.

Table 8: Summary of case companies and interview details

Company	**Stakeholder position**	**Point of contact**	**Duration of interview**
Company A	Maritime equipment supplier	1. Chief Operating Officer	60 minutes
Company B	Shipyard	1. Deputy Managing Director	95 minutes
Company C	Maritime equipment supplier	1. Manufacturing Network Manager	60 minutes
Company D	Shipping company	1. Board member and Operations Manager	95 minutes
Company E	Classification society	1. Business Lead, Maritime 2. Work Process Manager	60 minutes
Company F	Shipyard	1. Sales Manager Retrofit	90 minutes

3.5 Data collection

The companies that were chosen for the research are stakeholders in the maritime industry. Of the companies interviewed, two are shipyards, two are maritime equipment suppliers, one is a shipping company and the last is a classification society. More detailed information about the case companies will be presented in the case study findings in Section 4 and Table 8 provides an overview of their role in the maritime industry as well as information about the interviews.

A semi-structured interview style was preferred as it allowed for more flexibility for both the interviewer and interviewee to develop ideas and questions more widely on the issues raised in the research (Denscombe 2017; Ali et al. 2015). This approach enabled representatives from the companies working within the maritime sector to provide valuable insights into the topic at hand. The interviews were led by the researcher and followed an interview guide which can be found in Appendix A.

The information and knowledge shared through the interviews will contribute to further discussion on how ETO companies can utilise DTs to support the integration of remanufacturing in their supply chains. This case study approach is deemed helpful for several reasons. As CE strategies in the maritime sector are under-researched in academia (Milios et al. 2019), an exploratory study could be beneficial to seek new insights. Further, the regulation of remanufacturing depends on the industry in scope, so the experimental approach will allow for accounting business and policy challenges distinct to the maritime sector (Milios et al. 2019).

To achieve optimum use of time, an interview guide was developed ahead of time, see Appendix A. The interview guide was designed for the interviewer, outlining the topics to be covered during an interview (Adrodegari et al. 2015). The guide was sent ahead of time so that the interviewee could read about relevant information and get an insight into what was set to be discussed in the interviews. This way, the interviewees had time to prepare if they felt needed. The guide 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 and to prevent the debate from being interrupted by irrelevant conversations.

During the interviews, to facilitate the discussion and ensure that it stayed focused on the research topic, a PowerPoint presentation was created. The presentation included the relevant information and questions from the interview guide but was presented in a more visual format. This approach aimed to provide the interviewees with a comprehensive understanding of the topics being discussed. The presentation can be found in Appendix B.

Post-interviews, a transcript of answers to the predetermined questions were sent for validation. The participants were asked to review the statements and give feedback if something was wrongly interpreted, ensuring the robustness of our final findings after the literature findings and interviews (Milios et al. 2019).

Following the completion of initial interviews with all the case companies, a questionnaire containing the compiled list of factors and uncertainties identified during the first round of interviews was shared with each company via email. The purpose was to request their input in terms of ranking and recommendations regarding the DTs listed in Table 18. The document pertaining to the second round of communication can be found in Appendix C. This approach was employed to ensure the validation of the findings from the initial interviews, while also utilizing the rankings provided by each company to identify key factors and gain insights into the maritime industry's perception of relevant technologies for remanufacturing purposes.

3.5.1 Data analysis

In the research process, the activities of conducting a literature study and interviews can be seen as a cyclical process (Figure 2). The initial literature study was performed to develop the interview guide and conduct the first pilot interview. Upon identifying new information from the first interview, additional literature was consulted and the interview guide was subsequently improved. To ensure data reliability, the interview guide remained unchanged thereafter.

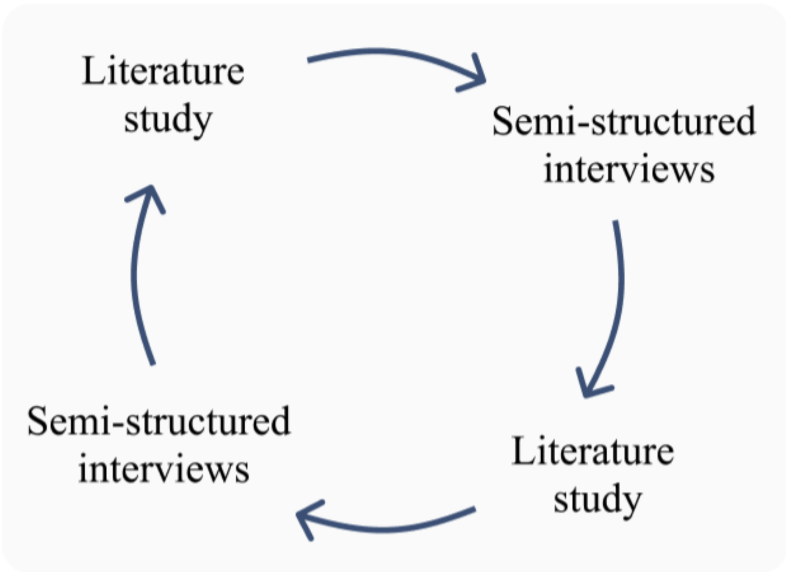

Figure 11: Methodological approach

The process of analyzing data is crucial to developing new theories (Eisenhardt 1989). The analytical approach in this study follows the two steps recommended by Eisenhardt 1989. The first step is within-case analysis, which involves gaining a thorough understanding of the results for each case individually. The second step is to search for cross-case patterns that allow for the generalization of conclusions. To test the hypothesis, empirical findings are compared with existing theories for each case. This is especially important in this study as it is based on a limited set of cases.

The list of influential factors determining the potential for remanufacturing was exclusively based on the findings obtained from interviews conducted over a period of time. The questionnaire presented the finalized list to the companies, allowing them to assign scores to each factor and thereby represent the importance of each factor from their perspective. Furthermore, the supervisor presented the list at a workshop for external maritime companies to validate the findings from the case study. The comprehensive list was also compared with the findings from the literature, which were explored after the list was completed.

3.6 Research limitations

This section will present the research limitations and in the following section, we will try to explain how the research quality is ensured.

3.6.1 Case study

Case studies offer valuable insights into holistic understanding, but they have limitations that can affect the reliability and validity of findings. Generalizing results from case studies to larger populations or other contexts can be challenging, especially when the study involves a small number of cases (Voss 2010). Additionally, case studies can be subjective, leading to inconsistent results due to researchers' varying interpretations and biases. The resource-intensive and time-consuming nature of conducting case studies can further add to these limitations, especially when collecting data from multiple sources and stakeholders. Analyzing qualitative data from case studies is also challenging, as it requires researchers to identify patterns and themes in the data, which can be subjective and impact the validity of the findings. Furthermore, the lack of control over variables in case studies can make it difficult to establish causality and draw definitive conclusions.

During the case selection process, specific requirements were set to decide which companies would be chosen. These requirements stated that the selected companies must have actively followed circular strategies and considered incorporating sustainable development principles into their operations. While all the companies met these criteria, their levels of experience and reflection varied significantly. Some companies had only started integrating repair and recycling activities, while others had more than 20 years of extensive experience in remanufacturing. The disparity in their knowledge foundation will pose limitations in comprehending and effectively responding to the posed questions.

3.6.2 Literature study

Whilst performing literature studies is a recognised method in scientific writing, there are still limitations to be aware of. The exclusion criterion was set only to include literature in English. This limits the literature study from including potentially valuable research published in other languages. Another limitation to acknowledge is the limited number of sources used. Here, only Scopus, Google Scholar, NTNU Oria and Web of Science were utilized in the identification process, thus limiting the research from including valuable literature not available from these resources. Selective outcome reporting is also a major threat to a literature study. The possibility of misleading interpretation of evidence outcomes in a literature study can have implications on the results and claimed research contributions.

The literature study is bounded by a set collection of keywords being present in the title keywords or an abstract of the document. Alternative terms such as ”closed loop” or ”zero waste economy” may also refer to similar concepts as CE. However, the search does not include other related terms to avoid potential disputes or misleading results. This is because there is no agreed-upon definition of CE, and other concepts such as ”cradle-to-cradle economy” and ”green supply chain management” have distinct differences. Only including literature that explicitly mentions CE ensures relevance and avoids subjective attribution of content. The resulting literature study thus presents a basic understanding and state-of-art within the CE field.

3.7 Research quality

According to Karlsson 2010, there are four specific criteria for assessing the quality of organizational management (OM) research: construct validity, internal validity, external validity, and reliability (Jünge 2022).

Construct validity is an important concept in research methodology that refers to the degree to which a measure accurately measures the concept or construct that it is intended to measure (Voss 2010). To establish construct validity, various forms of evidence have been utilized, including observations through interviews and documentation as data sources. The informants from the companies were able to review the transcript and summary of the interview. By doing so, the likelihood is that the findings presented in section 4 accurately reflect the case companies.

Internal validity means establishing an accurate causal relationship while avoiding other possible factors that could explain these relationships (Karlsson 2010; Jünge 2022). To maintain internal validity, various strategies were implemented, including the utilization of multiple case study designs to enhance validity. In addition, peer briefing can improve internal validity through sharing the research findings, interpretations and conclusions with peers to obtain feedback and criticism (Lincoln and Guba 1985; Jünge 2022).

External validity refers to the generalizability of research findings to other settings, populations, and situations beyond the specific context in which the research was conducted (Karlsson 2010; Jünge 2022). In other words, external validity pertains to the degree to which the results of a study can be generalized and applied to other settings outside the particular context in which the research was conducted. There are two forms of generalization: statistical generalization and analytical generalization (Yin 2009). Qualitative case studies employ analytical generalization, whereby researchers aim to extend the generalizability of specific findings to a broader theoretical framework (Jünge 2022). In the context of theory deployment, the analytical approach utilized in this thesis will compare the empirical findings with the theoretical findings, resulting in analytical rather than statistical findings.

Lastly, the criteria of reliability pertaining to the degree to which a study can be reproduced and yield identical outcomes (Voss 2010; Karlsson 2010). The objective is to minimize bias and ensure that comparable findings and conclusions can be obtained if the research is replicated by another researcher (Jünge 2022). The nature of case studies is context-dependent and rendering exact replication of outcomes is challenging. Therefore, maintaining reliability in semi-structured interviews necessitates the consistent use of an interview guide (Yin 2009). In this thesis, two interviewers conducted the interviews, presenting a challenge to the reliability of the present case study, as personal biases may influence what is observed, heard and recorded. To mitigate personal bias, case insights and findings were reviewed with supervisors and co-supervisors.

4 Case study findings

This chapter will introduce the case companies and present their respective findings. These results will then be compared and contrasted with the literature review's findings in the following chapter.

4.1 Introduction to the case companies

This section will present the case companies, outlining their products and primary operations. Company E, as a classification society, distinguishes itself from Companies A, B, C, and F, which are involved in the manufacturing of ETO products. Company D does not sell the ETO product they manufacture to an external customer and therefore also differentiates itself from the other companies.

4.1.1 Company A: Maritime equipment supplier

Company A is a leading manufacturer of propulsion systems and thrusters for a wide range of vessels, including ships, offshore installations, and aquaculture facilities. The company's main activities include the design, engineering, production, and service of thruster systems, propellers, and control systems. Company A's products either power the ships or keep them stationary and are designed to last the same lifespan as the ships the products are installed on, which is typically around 25 years.

4.1.2 Company B: Shipyard

Company B is a shipyard and shipbuilding company with a long history in designing and building innovative ships for a variety of industries, including offshore oil and gas, fisheries, and renewable energy. The company offers expertise in the areas of design, engineering, project management, construction, installation and commissioning. Company B will provide us with a perspective on the remanufacturing of vessels and onboard products while serving as the link connecting shipping companies and maritime equipment suppliers.

4.1.3 Company C: Maritime equipment supplier

Company C is a globally recognised equipment supplier specializing in advanced handling and lifting solutions. Their main activities include designing, manufacturing and supplying a wide range of solutions for the maritime industry. These solutions include cranes, winches, launch and recovery systems, and various handling systems. Company C differentiates its supply chain from the other case companies because they have outsourced its production to collaborative suppliers.

4.1.4 Company D: Shipping company

Company D is a shipping company that primarily focuses on its own fleet's operation and maintenance. The fleet includes six boats, with three actively deployed for fishing operations. The company engages in the distribution of various products, including fish and shellfish. Company D 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 Company D's extensive expertise in remanufacturing ships and maritime components, Company D is well-positioned to offer valuable insights from a shipowner's standpoint on the subject.

4.1.5 Company E: Classification society

Company E, a classification society, 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, Company E assists shipowners and operators in guaranteeing that their vessels satisfy international safety and environmental standards and are appropriate for their intended application. As mentioned in the case selection, Company E was included in the case study to provide a regulatory perspective. The desire for such a viewpoint arises from the stringent regulations imposed on maritime companies. Understanding classification societies such as Company E's perspective on the matter provided us with a broader understanding of the challenges that other companies face through their standards and requirements.

4.1.6 Company F: Shipyard

Company F is a renowned 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 excels in various services such as construction, repairs, rebuilding, and recycling of vessels. Showcasing a rich shipbuilding heritage, Company F has earned a reputation as a trusted and experienced shipyard. Company F's commitment to environmental management and quality assurance is evidenced by their ISO certifications, ensuring adherence to rigorous quality and sustainable practices standards.

4.2 Circular activities of today

This section will explore whether the case companies have integrated reuse, repair, remanufacturing, and recycling practices into their operations. This analysis will offer valuable insights into their current operational methods and their experiences with circular strategies. Furthermore, it will shed light on their attitudes towards circular strategies and remanufacturing, which will be discussed in more detail later on.

4.2.1 Company A: Maritime equipment supplier

CE strategies are a comprehensive discussion in Company A. The company's environmental footprint is most significant during the production and product use phases because the propulsion and thruster systems offered by the company are used throughout the entire lifespan of maritime vessels and therefore contribute to emissions.

At the end of the product's lifespan, the ship owner who possesses the product determines the disposal process. Typically, the product is scrapped, and the ship owner is compensated for the materials. However, Company A has observed that the scrapping process tends to prioritize material value rather than component value. Being a major equipment supplier, the company relinquishes ownership of the product upon delivery, resulting in a lack of authority or control over these procedures.

Currently, the company's circular strategies concentrate on repair as a standard approach to prolong product life. Repairs are typically performed at the ship's location, utilizing a combination of local staff and Company A's employees. In rare cases where a unit must be dismantled due to a major accident, the customer is usually given a new product. The old unit is remanufactured to satisfy new unit requirements, and the customer receives it as a backup if a similar situation occurs, or it can be installed in another vessel of the same customer. Although this is considered remanufacturing, these instances account for a small percentage of the company's annual volume of production, slightly above 2% or approximately five cases out of 200-300 units per year.

Regarding reuse, Company A acknowledges the value of the direct reuse of products and components but has yet to perform any reuse. The company currently have no recycling activities for its products. However, the company recognizes various materials that can be recycled, such as bronze, and expects that they will be appropriately handled during the scrapping or disposal of ships, although the process is beyond the company's supervision.

In conclusion, Company A's circular activities currently focus mainly on repairing products to extend their life. The company has limited circularity related to reuse and recycling, and some examples of remanufacturing. However, it is important to note that Company A is aware of the potential for circular activities and acknowledge the potential remanufacturing has in the maritime industry.

4.2.2 Company B: Shipyard

Company B has yet to adopt reuse practices in their own operations, they are aware of the various methods of incorporating reuse in the maritime market. Company B highlights examples such as shipowners selling their vessels for continued use rather than scrapping them.

To highlight the potential of product reuse, Company B points to the growing trend in Norway where older car ferries are being replaced with advanced electric ships. These retired ferries are finding new markets in Turkey, South America, and West Africa where there is high demand for used technology, indicating a growing second-life market for these ships. The fact that these ferries are being utilized for another 10-15 years after their initial use in Norway demonstrates the benefits of reusing products.

Company B is known for its expertise in the repair and maintenance activities of ships. The company offers several repair and maintenance services that can help to extend the life of a ship and avoid the need for a complete replacement. The shipowner has the freedom to choose between investing in a completely new system or opting for repair and maintenance services. Repair activities at Company B can include replacing specific components that are no longer functioning properly, checking that all systems meet current safety and environmental standards, and ensuring that the ship is in good working condition. By performing such maintenance work, Company B believes it can help to extend the life of a ship by another 10-15 years.

Company B currently has limited familiarity with remanufacturing practices. Remanufacturing can be a viable solution when a ship is not profitable in its current market or when there are no potential buyers for it. In such cases, the ship's hull can be preserved while the interior is modified to suit new purposes. This form of remanufacturing is most commonly employed when a ship needs to be adapted to a different market, where the interior can be altered to meet new requirements and needs. Company B has experience in converting platform supply vessels that were once used for offshore operations into fishing vessels, demonstrating an example of this type of remanufacturing.

Company B clarifies that once a ship is constructed and delivered to the customer, the shipyard bears no responsibility for its EOL phase. Company B states that "In the maritime industry, the decision-making process regarding the disposal of ships can be straightforward". By mentioning that ideally the ship should be sold for reuse or remanufacturing. However, in cases where the material value of the ship outweighs the value of reuse or remanufacturing, the ship is sold for scrap. This is often the case when steel prices are high, as there is a greater emphasis on recycling to take advantage of the value of steel. On the other hand, if steel prices are low, ship owners would prefer to keep the ship in operation by selling it for reuse or remanufacturing, particularly if the ship is of good quality and can continue to operate effectively.

4.2.3 Company C: Maritime equipment supplier

Company C, as a maritime equipment supplier, has experience with remanufacturing. Although these practices occur, they constitute a small part of the company's turnover and do not happen every year. When a crane is sold from one vessel to another, Company C acts as an engineering partner, performing thorough assessments, modifications, and adjustments to ensure optimal use of the crane in its new application context. This involves considering the requirements and specifications of the new boat, making changes to physical mounts, adjusting controls, and adapting systems. By carefully planning and engineering these adaptations, Company C ensures the transition of the crane to its new environment. However, due to the infrequency and limited demand for product remanufacture, the company's current utilization of reuse and remanufacturing is relatively low.

Repair is a significant part of Company C's aftermarket activities and represents an essential component of their work. The company handles repairs for customers when needed. While individual repairs may not contribute significantly to the company's total turnover, they are regularly carried out to ensure customer satisfaction and maintain the quality and functionality of Company C's products. Additionally, annual inspections are conducted to identify and address any potential issues early on, ensuring that customers benefit from the guarantee provided by Company C.

However, Company C has limited involvement in recycling processes due to their role as a supplier and lack of ownership over the products. Since customers own the products, they are responsible for managing the recycling at the end of the products' life cycles. Company C's business model relies on outsourcing and collaboration with external partners and manufacturers, which means they do not have direct access to the raw materials used in production. Given their limited control over the product lifecycle and raw materials, extensive recycling activities are currently not a significant part of Company C's operations.

4.2.4 Company D: Shipping company

Company D employs a variety of strategies to minimize waste and maximize the lifespan of components. Through a restructuring process spanning 15-20 years, the company has successfully repurposed 15 boats, currently operating with a fleet of three vessels. As part of their responsible approach, the company has conscientiously disposed of 12 ships by sending them for scrapping, while salvaging and storing components that meet quality standards in their warehouse. These salvaged components have been utilized in their three active operating vessels. As a result, Company D owns a substantial inventory of used products, comprising of everything from cost-effective to larger premium components.

Company D is the case company that has implemented the CE reuse and repair at the highest level, due to the fact that these practices are deeply integrated into the daily routines of this company. As an example, they have utilized a significant portion of the steel structure and hull from an old boat purchased from Iceland to construct one of their fishing vessels. This innovative approach combines new and used parts, resulting in a remanufactured fishing vessel, one of the first of its kind globally.

Currently, the majority of goods introduced into their supply chain consist of pre-owned items, with the notable exception of products deemed essential for safety or high-risk operations. An illustration of this practice can be observed in the operations of Company D, which effectively reuses steel cables and ropes once they have reached their intended lifespan, utilizing them in less demanding areas. Furthermore, the company engages in the remanufacturing of used cranes, employing processes such as sandblasting, hydraulic replacement, and repair work to restore the cranes to a pristine condition, similar to new units. The aforementioned instances are just a few among the numerous ongoing circular activities undertaken by Company D.

The company places a significant emphasis on repair and maintenance, dedicating a few days at a time to actively operating ships for these purposes. This regular maintenance routine is essential in prolonging the lifespan of the ship's components. If any parts on the vessels need replacement, the company relies on its extensive inventory of used products from its own warehouse to substitute the damaged components. However, it is important to note that the decision to use used products or opt for new ones depends on the specific product type and the level of safety or risk involved. The company mainly perform their own repair activities.

Although the specific methods employed by the company for recycling activities are not explicitly outlined, the company mentions other arguments that indicate a level of recycling undertaken when components cannot be reused, repaired or remanufactured. This is supported by examples provided, where used products that no longer meet the requirements for reintegration into the supply chain are instead sold for their material value, possibly indicating a recycling process. Additionally, the company's strong emphasis on incorporating recyclable materials into its products further reinforces the idea of its commitment to recycling practices.

4.2.5 Company E: Classification societies

Since company E is not a manufacturing company similar to the rest of the case companies their operation can not integrate reuse, repair, remanufacturing and recycling in methods comparable to the other companies. This section about Company E will therefore be based on their experiences working with maritime manufacturers.

One area where reuse can be seen is in the reselling and transfer of vessels between different owners. Ships can be reused and repurposed, finding new owners who can utilize them for various maritime operations. This aspect of reuse does exist, albeit not at a substantial level.

Repair, in the context of maintenance, is heavily employed within the maritime industry. Recognizing the importance of keeping vessels in optimal condition, shipowners and operators prioritize regular maintenance and repair to ensure the safe and efficient operation of their assets.

When it comes to remanufacturing, Company E observes notable instances of ship rebuilding or conversion, particularly in the case of tankers and offshore vessels. These conversions involve significant modifications and upgrades to the existing vessels, enabling them to serve new purposes or operate in different capacities. Company E acknowledges and supports such remanufacturing efforts within its classification and certification processes, but mentions that class societies such as themselves will not accept used items that cannot meet the regulations that new ones meet.

In terms of recycling, there are some practices observed in the maritime industry, particularly with regard to steel. Vessels that have reached the end of their operational life are often dismantled and scrapped, with the focus primarily on recovering the value of the materials. While recycling exists to a certain extent, it is primarily centred around salvaging valuable materials from decommissioned vessels.

4.2.6 Company F: Shipyard

Company F has implemented a comprehensive range of circular strategies, including reuse, repair, remanufacturing, and recycling, to effectively manage their operations.

Remanufacturing plays a significant role in the company's daily operations, accounting for approximately 50% of their activities. By focusing on remanufacturing, Company F extends the lifespan of existing vessels, enabling them to be repurposed and meet the specific needs of customers. This process involves collaborating closely with clients to determine engineering and design requirements, as well as executing the necessary modifications and upgrades on either the customer's existing boat or one procured by the shipyard.

The company also actively engages in ship recycling, which constitutes another 50% of their operations. Instead of disposing of EOL vessels, Company F employs environmentally responsible recycling practices. However, due to market dynamics, the demand for ship recycling has decreased while new construction has seen an upturn. Consequently, Company F focuses on finding innovative ways to recycle ships efficiently and diverting them back into operation whenever possible.

When considering remanufacturing projects, Company F collaborates with customers seeking to repurpose their boats for specific purposes. These conversions may involve transforming offshore vessels into fishing boats or modifying them to serve diverse industries such as offshore wind, oil, or fish farming. The shipyard addresses customer requirements by enhancing vessel capacity, integrating new equipment, and providing comprehensive upgrades.

The motivation behind operating ships after their end-of-life stage is driven by market conditions. As certain sectors, like oil and gas, begin to recover, there is a growing demand for vessels. In response, Company F helps ship owners revitalize their previously slated-for-recycling boats, ensuring they are fit for market use. While these vessels may appear worn from a distance due to a backlog of maintenance, closer inspection reveals that their hulls and equipment possess a substantial remaining lifespan.

When initiating a remodelling project, Company F prioritizes maintenance tasks alongside engineering and design activities. This parallel approach optimizes project timelines, allowing for efficient conversion and equipment installation before delivering the remanufactured vessel. Remarkably, the completion time for remanufactured projects, ranging from 3 to 6 months, stands in contrast to the lengthier timelines associated with new construction.

To facilitate the remanufacturing process, Company F employs a combination of new and second-hand equipment. Due to excessively long delivery times for new equipment, the shipyard incorporates quality, pre-owned components. This approach has yielded positive results, surprising shipping companies who have expressed satisfaction with the incorporation of used equipment. The shipyard leverages its extensive network to source equipment globally and even carries out in-house recycling of certain components, engaging original suppliers for refurbishment or software upgrades as necessary.

4.2.7 Challenges with integrating circular strategies

Although the case companies share the focus on innovation and sustainability, they face numerous challenges when it comes to implementing circular economy strategies. While this thesis does not aim to provide an extensive list of challenges, it is applicable to highlight the major challenges that surfaced during the interviews.

Company A is facing challenges regarding ownership of the product or component which is up for remanufacturing. They do not own the product they produce after it is delivered to the customer. This means they do not have access to the product or its history, making it difficult to know what can be remanufactured or reused, and which parts need to be discarded.

Case companies A, B, and C mentions that as a small player in a global industry, they are faced with a significant obstacle due to the absence of a regulated market for circular economy strategies. Company A mentions when talking about the integration of CE strategies, "There are no advantages, either for reputation or finances, which would indicate that such an implementation in the value chain is a logical choice.". Further, Company A emphasises the fact that the company is a small player in a massive global industry, which makes it challenging for the company to steer the market towards circular strategies without the cooperation of the wider industry.

Despite these challenges, Company A believes that several mechanisms can help promote circular strategies. International regulations, as well as common laws and regulations from classification societies, can establish standardized practices and create a more supportive environment for circular operations in the maritime industry.

One representative from Company E mentions that “The maritime business is extremely conservative. [They have the mindset of] if it’s working why should we change it? If you have money today, why should you make any changes?”. The classification company mentions that while they are part of the conversation, to drive the adoption of circular strategies in the maritime industry, there needs to be regulatory pressure. Regulations serve as a catalyst for change and encourage the development of new business models that incorporate circular strategies to meet these regulations and regulatory measures are often the driving force behind industry advancements.

Company E highlights the changes that were introduced in the case of emissions. When organizations like the EU implemented stricter requirements for reducing emissions and provided a clear pathway, the industry began to take action.

All case companies besides Company D mentions the rules and regulations as a major challenge for the company to integrate more CE strategies. Company D mentions that close collaboration with classification societies and experience with identifying which factors that determine the potential for reuse and remanufacturing makes it possible for the company to remanufacture used products today.

The next section will identify the key factors that determine the potential for remanufacturing, based on answers from the case companies.

4.3 Factors that determine the potential for remanufacturing

This section will discuss the factors that influence the potential to remanufacture a product. These factors have been identified by the case companies and organized into a table, including categories, specific factors, and descriptions for each factor.

After the initial round of interviews, the finalized list was circulated again for ranking. The aim was to determine which factors are most relevant when assessing the potential for remanufacturing. As the list evolved through an iterative process over time, the different editions of the list will not be presented in the results. Instead, the focus will be on the complete list and the rankings assigned by the companies after reviewing the finalized version. Furthermore, explanations will be provided for the presence of certain factors on the list by referring to examples and comments shared by the case companies during the interviews. This will help illustrate the rationale behind the current composition of the list.

4.3.1 Company A: Maritime equipment supplier

Company A, which manufactures thrusters and propulsion systems faces challenges related to the potential remanufacturing of their products due to various factors. Company A has ranked the different factors which can be found in Appendix D, the ranking will be used to indicate which factors that are most influential for the company.

One important factor for Company is the level of damage and level of fatigue that their products may incur. The interview highlights the significant damage caused by corrosion and exposure to ocean water, which can make remanufacturing difficult. These factors are both ranked high on the list of factors. The interview specifically mentions the corrosive effects of seawater, which may render certain components unusable after being submerged for 25 years. Along the line of conversation about damage and fatigue, the material composition was also mentioned. Whilst not crucial, the material composition of their thrusters is also an influential factor.

The technical lifetime of the thrusters is another important factor for Company A. With a 25-year usage period, the company must carefully evaluate whether remanufacturing can maintain the required performance and effectiveness over such a long lifespan. If remanufactured products cannot meet the desired standards in terms of quality, they may be deemed unsuitable for use. Further, Company A emphasized that it is crucial for remanufacturing to be an option, the company must be ensured that this is not at the expense of the product's quality or technical lifetime.

While the value of the product is not a factor that Company A regards as significant, the type of product is. Whether the component is mechanical, hydraulic, electric or software are factors that determine whether the company would consider remanufacturing. Examples during the interview were regarding electric products and the fast development of these types of products. Company A's products are built to last the lifetime of a ship and considering the fast development of electronic components to this day the components used will not be viable for lasting another 25 years as well as not meet the new standards and requirements that these products now face.

Ensuring operational efficiency is of paramount importance in determining the potential for remanufacturing. The interview indicates that new parts have the potential to meet specific standards that used components may not necessarily fulfil. Consequently, if remanufacturing fails to uphold the required operational efficiency, it might be disregarded in favour of opting for new products. A noteworthy example mentioned by Company A relates to the fuel efficiency of a recycled product, functioning at 99% of that of a new product. Given the intended usage duration of 25 years, even a 1% improvement in fuel efficiency can exert a significant influence on both energy consumption and the product's lifespan throughout an extended period.

Two more factors are regarded as highly influential for determining whether to remanufacture or not for Company A. These are the geographical location and the cost of operating. The distance between the used product and the location of Company A's manufacturing operation is highly influential for the company. During the interview, the company acknowledged that determining whether it is more environmentally friendly to transport a used product back to the factory for remanufacturing and then transport it back to the customer, as opposed to simply manufacturing a new one, poses a challenging dilemma for the company. Additionally, one must consider the transportation cost of such a procedure.

Lastly, in the case of remanufacturing propulsion and thruster systems for marine vessels, the cost of operating plays a significant role. The fuel efficiency of these systems directly impacts the operational costs for the customers who rely on Company A's products. Even a small reduction of just 1% in fuel efficiency can result in substantial economic burdens over the extended technical lifetime of these maritime products. Therefore, Company A recognizes the importance of optimizing the cost of operating their propulsion and thruster systems to ensure long-term customer satisfaction and maintain a competitive edge in the market.

4.3.2 Company B: Shipyard

During the interview with Company B, a shipyard company, several factors were identified that determine whether they choose to remanufacture or not. The ranking of the different factors can be found in Appendix E.

The most relevant factors include the level of damage and fatigue in the vessel. Extensive damage or fatigue can make remanufacturing less feasible compared to building something new. Company B mentioned examples of rust and wear and tear when talking about damage and fatigue. Further, another aspect close related to this is the material composition and material value. Material composition is particularly relevant in ships. Remanufacturing is more viable if the steel quality is good and there is enough steel remaining in the hull. However, extensive corrosion caused by water exposure can limit the feasibility of remanufacturing.

Material value contributes to determining whether to remanufacture, due to the fact that market prices per tonne significantly influence the choice between recycling and reuse, particularly in the context of ships, which are often sold based on their material weight. Company B highlights that remanufacturing is considered when it presents an economic advantage over recycling, ensuring that the total cost remains lower.

Another economic factor that is a crucial consideration is the cost of operations for a new product versus a used one and the cost difference between a new product and a used one. If remanufacturing proves more expensive, it may be more practical to build a new vessel. Company B provides an example where the total costs need to be below a certain threshold, usually around 70% of the cost of manufacturing a new product, for remanufacturing to be considered. Cost savings and economic advantages are key factors in the decision-making process. For instance, to highlight the cost of operations, Company B mentions that shipping companies prioritize propeller efficiency. They seek propellers that can match the efficiency of new products. A reduction of 10% in propeller efficiency could result in a 10% increase in fuel consumption, which has substantial implications in various aspects of operations, including economic

Technical specifications, such as the type of product, also influence the potential for remanufacturing. Electrical components are generally less suitable for remanufacturing compared to products made of steel and aluminium parts. Electrical components, which have a higher innovation rate and may become outdated quickly. Another factor that is related to the type of product is the placement of the product on the vessel. The location of the product on the vessel will determine which conditions the product has been operating in. If the product has been submerged in sea water for a long time it goes hand in hand with the level of damage and level of fatigue. Another aspect that Company B mentions when talking about product placement is the degree of accessibility for dismantling the product from the vessel.

Lastly, Company B emphasizes both the significance of designing products for disassembly and the importance of standardization of products. They highlight how Company B's boats are designed to facilitate the removal of components, enabling their replacement or repair, which is crucial for successful remanufacturing. Additionally, they note that standard production components are generally easier to use in remanufacturing, and they mention that certain boats designed by Company B are intentionally created to accommodate changes in their life cycle, allowing for the straightforward replacement of major components. Designing vessels for disassembly is beneficial, as it allows for easier replacement or upgrade of components without extensive modifications.

4.3.3 Company C: Maritime equipment supplier

During the interview with Company C, several factors that could influence the decision to remanufacture were discussed. Company C offers a unique perspective on remanufacturing due to its extensive outsourcing of production activities. Company C score for the different factors can be found in Appendix F.

One key point emphasized by Company C is the importance of conducting a comprehensive preliminary project to map out the remanufacturing process before commencing any project. Factors such as transferability, technical complexity, the condition of the product, and the product type are crucial considerations during the initial stages of a remanufacturing project. Cost factors also hold significant weight in Company C's evaluation of the potential for remanufacturing. They carefully weigh the cost difference between a new product and a used one before making a decision.

The condition of products and components emerged as critical factors in the discussion, taking into account both the level of damage and fatigue. Company C evaluates the condition of various components within one of their product, such as a crane, to determine the product's overall state. They pay particular attention to the expensive components of the most critical parts. If these are not in the required condition the company mentions that the likelihood of remanufacturing is negatively affected. Furthermore, the level of fatigue is more heavily discussed due to the materials Company C uses in their products, while the company does not have concerns when it comes to materials like aluminium, which are more susceptible to fatigue over extended periods of use. By comparing the condition of the expensive critical components to the condition of the smaller less critical ones, they can make an informed decision whether the condition of the used product is at the required level for remanufacturing.

During the preliminary project assessment, product documentation plays a vital role. Company C emphasizes that the availability of comprehensive documentation is considered essential for remanufacturing. Proper documentation is especially important for Company C, due to the strict regulations put upon lifting equipment such as cranes. For the remanufactured product to be certified, the need for product documentation is vital to ensure the longevity of the lifting equipment so that the products are adhering to regulations for safety and quality standards.

4.3.4 Company D: Shipping company

When determining the potential for remanufacturing, Company D takes several factors into consideration. In Appendix G you will find an overview of how the company has ranked each factor. Since Company D have many similarities to the answers of the other case companies the following paragraphs will also highlight the answers that stick out and are specific to Company D.

When considering the purchase of used components for remanufacturing, Company D takes into account factors such as the level of damage and fatigue. Extensive rust and fatigue to the main structure are typically deal-breakers. However, they may still consider purchasing smaller parts that are part of larger components. They try to avoid components that are obsolete or have parts that are impossible to find, although they can manufacture some parts themselves in their workshop. Surface rust is one example of the damage that is of lesser concern to them, as they have a sandblasting hall to perform the necessary maintenance for the component to look brand new.

To evaluate the condition and quality of the used product, Company D does a physical inspection and checks for product documentation. They obtain product documentation from the scrapyard, including information about the original owner and the condition of the equipment. In some cases, product documentation is mandatory, depending on the specific component and the regulations imposed by authorities. Making quality, product documentation and regulations crucial factors for Company D when determining whether to remanufacture or not.

Although the material value is not a factor that Company D highly regards, the material composition is important for the company. They prefer materials that can be recycled and have a longer service life. For example, stainless steel components are favoured due to their durability and resistance to rust, which is crucial in the harsh marine environment in which they operate.

Another consideration is economic factors considering product cost. Here the company mentions that the cost of operations, the cost difference between used and new, and the value of the product are factors that are highly influential when determining used products for remanufacturing. The company usually have a threshold of about 70% give and take, determined by the type of product it is. If the product is critical and related to security, they want to ensure that the reused component is as good as new to remain the desired level of performance and reliability. If the cost of remanufacturing a product exceeds this limit of 70%, the company prefer to purchase a new product instead due to the added uncertainties that come with a used product.

Product structure is also a factor in their decision-making when determining potential. Company D considers the design for disassembly, aiming to have components that can be easily disassembled and reassembled. They also prioritize the transferability of equipment, aiming to standardize components across their fleet to minimize the need for different spare parts.

While the placement of the product on the vessel is not crucial for determining the potential for remanufacturing, Company D is more conservative on the geographical location of the used product. Company D prefers to source used products from scrapyards that are relatively close to them and certified. They want to ensure that the sources are reliable and reputable. For example, they avoid buying from scrapyards in distant locations, such as the beaches of India.

4.3.5 Company E: Classification company

Company E, the classification society, considers a different perspective when determining the factors that influence whether to remanufacture or not. Company F's scores can be found in Appendix H. Whilst Company E also considers level of damage and fatigue as one of the most crucial factors, this will not be heavily highlighted in this section to avoid repeating arguments.

The classification company considers the product documentation of the history of the product to be a significant factor. Having proper documentation and knowledge about the product's usage, maintenance, and original construction is essential for Company E to accept and support reuse and remanufacturing initiatives. Safety and quality are significant considerations, and the availability of detailed information about the product's history and compliance with applicable requirements is vital. The decision-making process also takes into account how the product has been used and maintained. Maintenance records and operational logs provide valuable information about product lifetime and durability. To highlight these factors, Company E states,

> When considering the use of remanufactured products, it is crucial to ensure that they meet the same safety standards as new products. This factor holds significant importance. To achieve this, we require detailed information about how the products or components were originally built, the applicable requirements, and whether third-party verification was conducted during the manufacturing process. We also need information about the product's operational history, including how it was maintained. These details play a vital role in our evaluation. If we have access to this information, we can confidently consider remanufacturing the product.

The design of vessels is also mentioned, Company E emphasise the need for a more modular approach to ship design to accommodate evolving technologies and industry demands as well as designing products for disassembly and incorporating standard components facilitate the remanufacturing process. While designing for flexibility may increase costs, it is considered important due to uncertainties in regulations and fuel prices.

When it comes to prioritizing which components have a higher potential for remanufacturing, Company E focuses on the type of products that are not safety-critical equipment and components related to the vessel's safety. The remaining product lifetime, areas of fatigue, and the regions where the vessels have travelled also influence the potential for remanufacturing. Corrosion and water damage can hinder the remanufacturing of certain components. Standardization of components is preferred as it simplifies finding compatible vessels for remanufactured products. A product's original cost and value, as well as overall operational costs and maintenance, are considered when evaluating remanufacturing options.

Lastly, based on experience and stakeholder feedback that Company E, components with greater potential for remanufacturing are those that offer safety guarantees, economic viability, and reliable access to spare parts. Company E mentions steel structures as promising components for remanufacturing.

4.3.6 Company F: Shipyard

Company F, a shipyard company, has found many of the factors relevant for determining remanufacturing potential, the company's answers can be found in Appendix I.

Company F places the highest importance on the level of fatigue and compliance with regulations. Fatigue level indicates the condition and remaining lifetime of the equipment, and critical fatigue may require additional investments in control units or electronic components.

Part of adhering to regulations is the need for product documentation. These can be from original drawings from suppliers, original certificates and knowledge about the product use phase such as running time. Company F highlights the importance of product documentation and expresses that obtaining the necessary certificates and manuals for a used product is crucial when purchasing a boat or equipment from scrapping. While certification retention periods exist, finding crucial documentation becomes increasingly problematic, particularly when it comes to critical components such as rescue equipment.

Compliance with regulations, particularly those set by classification societies such as DNV, is essential for ensuring the product meets safety and operational standards. Company F emphasizes the constantly changing nature of rules and certification in the maritime industry. An example is when introducing old and used equipment on a boat requires careful consideration of the applicable rules based on the keel laying date of the boat. If the equipment does not possess the required certification for the specific year, it cannot be used. Company F also highlights that not all sellers and scrapyards are able to provide the required documentation, as the history and documentation often remain with the original shipping companies, which may no longer be involved. While the maintenance system on board logs the product history this data is usually not accessible through the scrapyards and sellers of the used components. Company F expresses the need for legislation and processes to re-certify older components, as the absence of such measures prevents the reuse and remanufacturing of certain equipment.

Damage level and product documentation play a crucial role in determining the potential for remanufacturing for Company F, the technical lifetime and availability of standard components simplify the process. Company F identifies technical lifetime as a maintenance-oriented term. they explain that while a used product may have a designated lifetime of, for example, 50 years, the technical lifetime can be no longer than 10. On the other hand, Company F mentioned that they found a 20-year-old compressor that was only used for 20 hours, so based on the running time of the product was as good as a new one.

Company F also takes into consideration other factors that influence the decision, though with slightly reduced significance. These factors include the geographical location of the product, placement of the component within the vessel, material composition, material value, cost of operating used equipment compared to a new, cost difference between new and used products, product/component value, and design for disassembly. The geographical location is considered for large components due to potential shipping costs. The placement of the component within the vessel affects extraction ease. Material composition and value, along with the cost comparison between new and used equipment, help determine the financial feasibility of remanufacturing. The value provided by the product or individual components and the design for disassembly also plays a role in the decision-making process.

4.3.7 Factors that determine the potential for remanufacturing

In this section, the result of the ranking performed by the case companies will be presented in Table **??**. In this table, the scores given to each factor from each company as well as an average score are included. This table will be used in the discussion of the next chapter.

It has become evident that numerous factors play a significant role in assessing the potential for remanufacturing a used product. According to the information gathered from interviews conducted with the case companies, a total of 22 factors were identified. These factors encompassed various aspects related to product condition, location, technical specifications, external factors, product cost, product structure, and product performance.

In order to determine which of these factors is more influential in assessing the potential, the companies were asked to assign scores ranging from 1 to 5, with 5 indicating the highest relevance and 1 indicating the lowest. To differentiate the factors which are most influential in the decision-making, average scores for each factor were calculated. The formula used is provided below. In this formula, the numbers 1 to 6 correspond to companies A to F.

$$Average\ score = \frac{1}{6}\sum_{i=1}^{6} x_i = \frac{1}{6}\left(x_1 + \cdots + x_6\right)$$

The chosen threshold of 3 was based on the scoring system provided to the case companies, where scores ranged from 1 to 5. Factors with an average score above 3 were considered relevant, suggesting a consensus among the case companies on their importance in the remanufacturing decision. According to the results, there are a total of 16 factors in this category, with five of them having an average score of 4 or higher. These five factors are deemed highly relevant in the decision-making process regarding the remanufacturing of used products. The top five factors identified by the companies are:

- Level of damage (score = 4)
- Level of fatigue (score = 4.667)
- Regulations (score = 4)
- Cost of operations for a used product vs. a new. (score = 4.333)
- Quality (score = 4)

These top-ranking factors offer valuable insights into the decision-making process for remanufacturing a used product in the maritime industry. The factors "Level of damage" and "Level of fatigue" emerged as key considerations across multiple case companies. These factors are intertwined, as the level of damage can significantly impact the product's fatigue and overall remanufacturing potential. Moreover, regulations were consistently emphasized, reflecting the complex regulatory landscape that companies must navigate when engaging in remanufacturing activities.

Furthermore, Figures 12 and 13 visualize a variation in the scores between case companies. These provide interesting insights into the diverse perspectives and priorities within the maritime industry. Each company represents a different stakeholder, such as maritime equipment suppliers, shipyards, shipping companies, and classification societies. The variations highlight the unique considerations and priorities associated with different roles in the industry, shedding light on the multifaceted nature of the decision-making process.

The remaining 11 factors, which also had average scores above 3, encompassed various aspects such as material value, product documentation, type of product, technical lifetime, innovation rate, the cost difference between new and used products, standard components, transferability, technical complexity, fuel efficiency, and operational efficiency. The specific perspectives of each case company on these factors provide additional insights into the complexities and considerations involved in assessing the potential for remanufacturing. The variations in the 16 factors will be further discussed in Section 5.2.

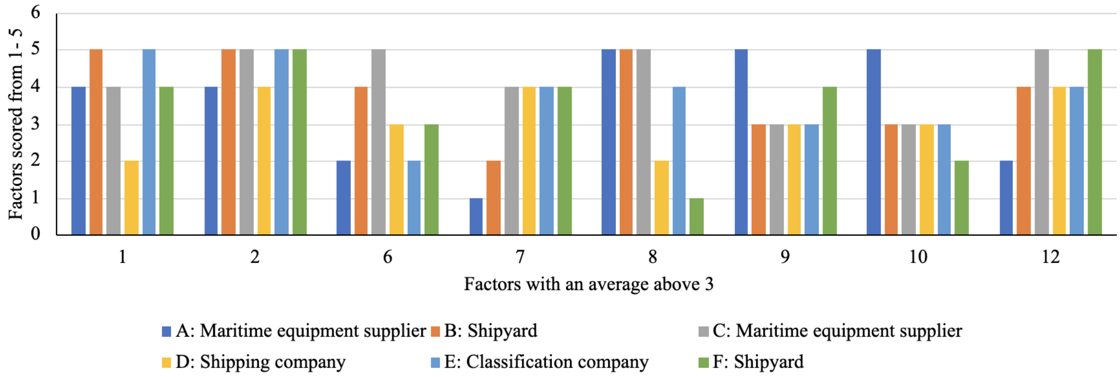

Figure 12: Significant factors

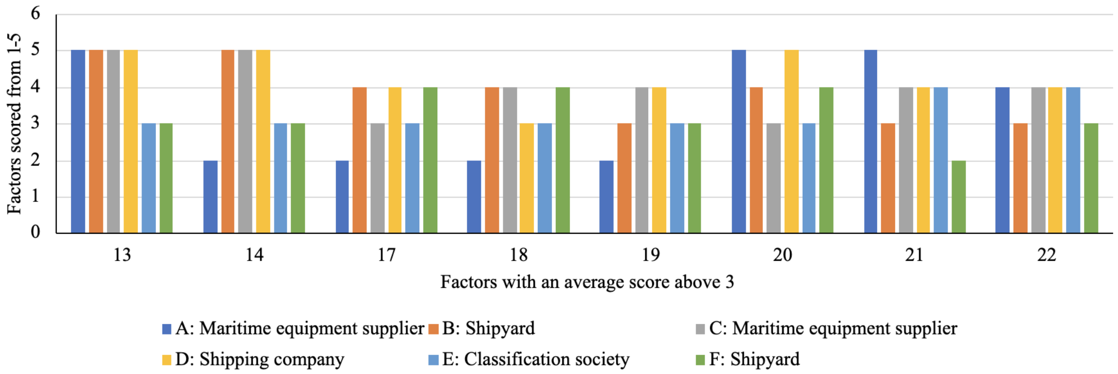

Figure 13: Significant factors

Categories	**Factors**	**Description**	**A**	**B**	**C**	**D**	**E**	**F**	**AVG**
Product condition	Level of damage	Extent of rust, corrosion, or other forms of deterioration.	4	5	4	2	5	4	4
	Level of fatigue	Extent of material fatigue due to wear from operation.	4	5	5	4	5	5	4.667
Location of product	Geographical location of product	Distance from product to factory.	5	1	1	4	3	3	2.833
	Product placement on vessel	The degree of accessibility for dismantling a product from the vessel is determined by the physical location of the product.	2	4	2	3	3	3	2.833
Technical specification	Material composition	Specific types and proportions of materials or substances used in product.	2	3	2	4	3	3	2.8333
	Material value	Value of material.	2	4	5	3	2	3	3.1667
	Product documentation	Overview of product history (Maintenance reports, overview of routes).	1	2	4	4	4	4	3.1667
	Type of product	Mechanical, hydraulic, electric or software.	5	5	5	2	4	1	3.6667

	Technical lifetime	Refers to the duration a product remains to be technically reliable and capable of fulfilling its defined scope of purpose.	5	3	3	3	3	4	3.5
	Innovation rate	Product technology remains current and up to date for multiple product lifecycles	5	3	3	3	3	2	3.1667
External factors	Established remanufacture process	An established systematic method for handling reverse flow and remanufacturing activities.	2	2	3	3	3	2	2.5
	Regulations	Regulations that govern maritime operations (classification society, EU..).	2	4	5	4	4	5	4
Product cost	Cost of operations new product vs. used	The cost of operating a new product vs. Operating a remanufactured one.	5	5	5	5	3	3	4.333
	Cost difference new product vs. Used product	Cost of manufacturing a new product vs. Remanufacture as used one.	2	5	5	5	3	3	3.8333
	Product/component value	Where the product is on the specter from premium to low-cost product	1	2	3	5	3	3	2.8333
Product structure	Design for disassembly	Design for disassembly and separation.	1	3	2	4	3	3	2.667

	Standard components	Interchangeable components.	2	4	3	4	3	4	3.333
	Transferability	Extent to which a product meets the necessary compatibility requirements for successful transfer to a different location or system.	2	4	4	3	3	4	3.333
	Technical complexity	Degree of intricacy and sophistication of its technical aspects, including component count, interdependencies, and specialized knowledge needed for assembly or maintenance.	2	3	4	4	3	3	3.1667
Product performance	Quality	Degree to which the product meets requirements and standards.	5	4	3	5	3	4	4
	Fuel efficiency	New product vs. Used product.	5	3	4	4	4	2	3.6667
	Operational efficiency	Compatibility with performance range of product.	4	3	4	4	4	3	3.667

Table 9: Factors identified to determine the potential for remanufacturing and their given scores from case companies.

4.4 Identified uncertainties that remanufacturing bring to the supply chain

This section presents the findings from interviews conducted with five companies operating in the maritime sector: Company A (maritime equipment supplier), Company B (shipyard), Company C (maritime equipment supplier), Company D (shipping company), and Company F (shipyard). The interviews aimed to explore the potential integration of remanufacturing activities and understand the associated supply chain uncertainties categorized after uncertainty source supply, process, demand, and control.

It is important to note that Company E, classified as a non-manufacturing company, did not participate in this particular section of the case study. This decision was based on the fact that the company does not possess a supply chain involving manufacturing activities. Since the questions specifically focused on the uncertainties related to integrating remanufacturing into the company's supply chain, Company E was deemed less relevant and therefore not included in the questioning.

To initiate this section, it is imperative to highlight a remark made by Company F on supply chain management with remanufacturing strategies.

> It is not a normal supply chain, you cannot take the textbook on supply chain and then introduce this type of activity [...]. Because it's not off the shelf and not a new certified product. You have to have the expertise to make it work.

4.4.1 Supply uncertainties

The interview responses revealed several supply uncertainties when integrating remanufacturing activities into a maritime supply chain. These uncertainties include raw material availability, supply lead time, used product availability, quality of used product, collection procedure, transportation lead time, and variation in the quality level of used products. Each company offered unique insights into these uncertainties, highlighting different challenges and perspectives. Which uncertainties the company identified are visualized in Table 10.

Table 10: Supply uncertainties identified by case companies

Uncertainty source	Uncertainty	Company
Supply	Raw material availability	A, B, D
	Supply lead time (schedule adherence)	D
	Used product availability	A, B, D, F
	Quality of used product	A, B, C, D, F
	Collection procedure	A, B, D
	Transportation lead time	D, F
	Variation in the quality level of used products	C, D

Companies A, B and D emphasized that raw material availability was important. Company A mentioned while steel-based products were readily available, electronic components posed a significant challenge. The scarcity of electronic components after 25 years of operation that is viable for remanufacturing was low and directly due to the fact that these products usually are outdated with the level that electronics and technology have been evolving over the last couple of decades. This affects the availability of used products.

Company B shed light on the scarcity of used products available for remanufacturing, in Company B's case this was ships. Company B said that:

> I think the biggest challenge with remanufacturing will be the supply part. If you want to remanufacture a ship, then you have to have available used products that you can remanufacture.

Although numerous shipping companies expressed interest in purchasing used vessels for remanufacturing purposes, identifying sellers proves to be a challenge. Unlike the centralized platform in other consumer markets, such as eBay, the maritime industry lacks an established marketplace for buying and selling ships, making it difficult to connect buyers with sellers. Company B suggested that improving access to available ships and facilitating connections between buyers and sellers could enhance the supply of used products for remanufacturing. The availability of used boats suitable for remanufacturing is uncertain due to the lack of a stable supply in the market. This is caused by the fact that shipping companies are not actively selling their used boats, making it difficult for those who want to use remanufacturing to find suitable boats.

Company F also underscored the accessibility of used products. In this context, they highlighted the availability of used products, which can be attributed to the limited trust placed in scrapyards nowadays. Furthermore, they emphasized that purchasing used products relies heavily on accumulated knowledge and expertise over time. Company F buys equipment and ships from shipyards all over the world including South Asia, and stresses the fact that it is difficult to determine whether one can trust the sellers from these areas. Company C disagreed with the rest of the companies and said:

> Access to used products will not be an uncertainty since if remanufacturing is to be relevant today, it must be that the customer comes to Company C with the desire for such a project to be carried out.

Talking about that for the company to perform remanufacturing activities the customer would have to come to them with a used product which originated from the company for Company C to initiate such activities.

All companies highlighted the quality of used products as a significant uncertainty. Company C mentioned the variation in condition among returned components, necessitating preliminary projects to assess feasibility, cost, and component suitability for reuse and remanufacturing. The primary objective of these initial assessments is to ascertain which components can be utilized, which ones cannot be used, or determine the ones that require discarding. Company F mentioned that each remanufacturing project is unique due to the large variation in the used product they use for the remanufacturing of ships. According to Company D, ensuring the availability of used products that meet the required quality standards and are compatible is crucial for both the availability of used products and the overall quality of the remanufactured products. Company C stressed the potential variation in the quality of used products:

> There can be a very large variation in returning products. Here, a preliminary project must then take place that maps what is to be done, and what it costs, and check the condition of the components that are returning to map what can be used and what cannot be used.

Company C meant that developing robust inspection and evaluation processes to identify viable components would reduce uncertainties associated with varying quality levels. Company A agrees with the development of such processes but mentions that:

> Identifying the history of components is a problem.

Referring to during the customer product use phase, the supplier lacks control over the product's operations. However, when the product is returned for remanufacturing, it becomes important to trace the product's operational history. Identifying the history of the product after it has been in operation is crucial to determining whether the product can be remanufactured, and could provide information on what maintenance has been performed on the used product.

Company B highlighted the challenges associated with the collection procedure for used boats. Unlike centralized platforms where cars are gathered from various brokers, the fragmented nature of boat sales requires potential buyers to contact multiple brokers individually. This lack of a centralized platform complicates the collection process and increases lead time. Company F mentioned that the transportation lead time of used products also can challenge the supply chain of ETO manufacturers. The company mentions an example of a 500-ton crane the company is currently trying to transport from the United Arab Emirates (UAE), which has shown to be a complex and difficult task.

4.4.2 Process uncertainties

In Table 11, the following process uncertainties identified based on the interview responses can be found. These were yield and quality, processing times, machine availability, labour resources, change in production, and lack of competence in remanufacturing.

Table 11: Process uncertainties identified by case companies

Uncertainty source	**Uncertainty**	**Company**
Process	Yield and quality	B, D
	Processing times	C, D, F
	Machine availability	D
	Labor resources	B, D, F
	Change in production	B
	Lack of competence in remanufacturing	B, D, F

The companies highlighted the importance of assessing the quality and condition of components to determine their potential for remanufacturing. Company C expressed concerns about unpredictable changes that may arise during the remanufacturing process, leading to delays and the need for ordering additional parts. This uncertainty regarding the quality and condition of components can impact the overall yield of remanufactured products.

Several companies acknowledged that processing times can be influenced by the uncertainty associated with remanufacturing. Companies C and F mentioned the difficulty in predicting the extent of work required to complete the remanufacture job and the potential delays caused by ordering replacement parts with long delivery times. This delay can affect the overall production schedule and lead to customer dissatisfaction.

The companies recognized the significance of skilled labour resources in remanufacturing. Company B indicated that the work required for remanufacturing varies from ship to ship leading to uncertainties in determining who should perform which tasks. Company F highlighted the need for resources with both specific and wide diversity in expertise, due to the large variations and unique character each project has. The availability of skilled personnel who possess the necessary expertise in remanufacturing becomes crucial for executing these activities efficiently.

Furthermore, Company F underscores the significance of expertise in remanufacturing throughout the remanufacturing operations of the company. They emphasize that successful remanufacturing operations require employees with exceptional skills and experience, not only in sales but also in purchasing. Unlike purchasing new equipment where a purchasing assistant can handle the process based on specifications, the procurement of used components is far more intricate. It demands a higher level of expertise to accurately assess and understand what needs to be purchased and the quality of the items. Lack of competence in remanufacturing can affect the quality of the final product and increase the risk of errors.

The integration of remanufacturing activities may require adjustments in the existing production processes. Companies A, D, and F expressed confidence in their ability to adapt to these changes, as they have integrated their manufacturing activities. Company F stated when answering how to adapt production when each project is unique,

> We don't have serial production or standard products, so this is not a problem. The remanufacturing is performed with what is available.

While Company B mentioned that the production of new construction is a predefined set of activities, with remanufacturing it is not. Company B representative stated,

> We know what to do, when, how and why, and who's going to do it. When it comes to remanufacturing, it is up to the status of the product you collect.

Emphasising the potential need for restructuring and reorganizing production processes can introduce uncertainties.

Company D highlighted that many suppliers and manufacturers are not equipped to handle remanufacturing jobs. They often lack a dedicated service department or the expertise needed for remanufactured components. This lack of competence and focus on remanufacturing within the industry may hinder the availability of reliable remanufactured products.

4.4.3 Demand uncertainties

The integration of remanufacturing activities in the maritime industry is subject to a range of demand uncertainties, as revealed through the interviews. These uncertainties encompass meeting customer requirements, considering quantity, aligning product specifications with customer preferences, adapting to changing customer preferences, navigating market competition, addressing customer quality requirements, managing customer perception of remanufactured products, and economic downturn. The identified uncertainties can be found in Table 12.

Table 12: Demand uncertainties identified by case companies

Uncertainty source	**Uncertainty**	**Company**
Demand	Quantity	A, F
	Product specification	A
	Change in customer preference	A, C, F
	Market competition	A, B, F
	Customer quality requirements	A, B
	Customer perception (used products vs. new products)	A , B, F
	Economic downturn	F

One of the key findings is the significant influence of customer preferences and perception of used products for remanufacturing activities to succeed. Company A emphasized the importance of customer acceptance and their willingness to consider products containing used components. The representative stated,

> The big problem is on the customer side. What will be the customer preferences, what will the customer accept from the reuse of materials? If the customer is not guaranteed a product that is as good as a new one today, the customer will not accept it.

While Company F's experience is that customers are not aware of the possibilities with remanufactured products. The companies note a positive shift in the customer's perception when they realize the cost advantages of obtaining parts at a fraction of the price of new products. Company B emphasized that demand for new construction tends to be more appealing than remanufactured vessels in the maritime industry. This preference stems from concerns about the adaptability of remanufactured vessels to their intended activities. Company B explained when discussing the demand uncertainties in regards to remanufacturing:

> Not because a remanufactured vessel is dated, but because it's not adapted to the activity it's supposed to do 100%.

This uncertainty stems from the customer's preference for new vessels and the challenges associated with ensuring that remanufactured vessels meet specific activity requirements.

Furthermore, Company F emphasizes that demand for remanufacturing has evolved over the years. The company mentions that two years ago, demand for remanufacturing was nearly nonexistent due to the downturn in the oil industry and the impact of the COVID-19 pandemic. Company F sees that with the recovery of the oil market, demand has surged while the supply of used products remains limited. Which noted by Company F has led to rising prices and a scarcity of available used products in the market. Several of the case companies mentioned oil prices as uncertainty regarding the economic downturn which influences the demanded quantity.

Another uncertainty highlighted by the case companies was market competition. Company C suggested that market competition would not be a significant uncertainty as customer interest drives the integration of remanufacturing activities for the company. Furthermore, the involvement of the original manufacturer in the remanufacturing process was highlighted, emphasizing the role of design ownership and the requirement to maintain certification from classification societies. This was emphasised by the representative from Company C stating,

> If it is our design, then there is no one else who can remanufacture the product if you are to keep the certificate that classification societies have issued.

In terms of market competition, Company F recognizes their leadership position in the shipyards sector for remanufacturing. However, in the sales of remanufactured equipment, the company mentioned companies from Denmark and parts of Asia, which are longstanding players who have excelled in selling used and remanufactured products.

Additionally, Company F mentioned that the customer base has undergone a shift. Previously, they primarily attracted customers seeking cost-effective solutions and operating in the low-end market segment. However, there has been a notable change, with more high-end customers entering the remanufacturing market. This shift is driven by factors such as limited access to new equipment, long delivery times, and a strong focus on cost efficiency. The economic downturn and the need to optimize every penny spent have forced high-end offshore companies, previously accustomed to purchasing new equipment, to consider remanufactured alternatives. Which has further influenced the uncertainty on demand, and more specifically the quantity.

Meeting customer quality and lifetime requirements emerged as a critical demand uncertainty in the interviews. Company A emphasized the need to ensure that products with used components meet the same quality and lifetime standards as those with only new components. However, tracking the history of components with a long lifespan and providing material certificates pose challenges. Identifying the history of components, particularly for material certification, was identified as an issue.

4.4.4 Control uncertainties

Lastly, the supply chain uncertainties identified with introducing remanufacturing are control uncertainties. These include the accuracy of assessing the used product, the economic feasibility of remanufacturing, forecasting method, lack of control of the original supplier, and remanufacture planning with the supplier network. The identified uncertainties are presented in Table 13.

Table 13: Control uncertainties identified by case companies

Uncertainty source	Uncertainty	Company
Control	Accuracy of assessing the used product	B, C, D, F
	Economic feasibility of remanufacturing	C, D
	Forecasting method of returned products	D, F
	Lack of control of the original supplier	B, C, D, F
	Remanufacture planning with the supplier network	C

One significant uncertainty in integrating remanufacturing activities is the control over accurately assessing the condition and compatibility of used products. Company F identified the uncertainty of the possibility to underestimate the extent of a project, leading to longer-than-expected processing times and delivery times. This can occur when the complexity and scope of the project are not accurately assessed in the start phase of the project, which can cause delays in the overall process. The company, for instance, have experiences where a used product was not accurately assessed leading to a one-month delay on the project. Similarly, Company C emphasizes the importance of aligning production and ordering materials to avoid delays, highlighting the uncertainties associated with assessing the required work for remanufacturing accurately.

Determining the economic feasibility of remanufacturing introduces uncertainties related to pricing strategies and cost considerations. Company C emphasizes the challenges of establishing appropriate pricing for remanufactured products, particularly when relying solely on hourly rates. They recognize the potential for suppliers to benefit more by intentionally prolonging the remanufacturing process. The interviewee stated,

> Basing the price only on an hourly rate would result in the supplier earning more by performing the work more slowly.

Company B, on the other hand, utilizes a hybrid contract solution with fixed prices and additional hourly rates, acknowledging the difficulty in accurately predicting the extent of the remanufacturing job.

> An example is that when we go into a new build project it is based on a fixed price. When it comes to remanufacturing, we have a hybrid contract, so there is one part that is fixed price and another part that is something called open-book or pay-for-hours, where the customer has to pay for the time we use plus

> margin. The reason is that there is a lot of uncertainty about what kind of work is needed to remanufacture, these processes vary from vessel to vessel.

These instances underscore the uncertainties associated with accurately assessing the used product and determining fair pricing policies.

The lack of control over original suppliers of remanufactured products introduces uncertainties in the supply chain. The long life cycles of martime products and vessels introduce uncertainties in sourcing the original suppliers of used products. Company D, which has extensive experience in sourcing used products from certified scrapyards have faced challenges with sourcing the original manufacturer of the products. Issues such as missing product documents or the original manufacturer no longer existing due to mergers, bankruptcies, or other factors contribute to uncertainties in obtaining necessary parts, information, and materials for remanufacturing. This can cause delays in the remanufacturing process and result in higher costs.

Another aspect of supplier uncertainty is one Company C experiences due to their production activities being outsourced to other suppliers. Planning remanufacturing activities within their supplier network introduces uncertainties related to coordination and communication. Company D has also experienced communication issues tied to sourcing original manufacturers of products.

Forecasting demand in a constantly changing market poses a challenge for Company F. They rely on their expertise and in-depth market knowledge to speculate on demand. An example mentioned during interviews is when they come across available equipment, such as cranes, they purchase it based on their anticipation of demand. While they may not know the specific buyer, they are confident that someone will be interested in acquiring the product. However, they also acknowledge the need to continuously monitor the market.

As previously mentioned the long delivery times of new components have increased the demand for remanufactured products, so as new component production increases and new products meet global demand, the delivery time for new products decreases. In such scenarios, the ability of Company F to sell its inventory of used equipment might encounter challenges, underscoring the significance of aligning its forecasting to prevent products from remaining idle in its inventory.

4.5 The use of digital technologies to address the uncertainties

Based on the findings of the second round of interviews, the companies provided suggestions for DTs that could be utilized to address the uncertainties identified during the first round. The tables below present the recommendations from the case companies based on the identified uncertainties.

The list below is the technologies that can be found in Table 19 in section 2.4.

1. Automation and industrial robots
2. Additive manufacturing
3. Cyber-physical systems
4. Data analytics
5. Integration of It systems
6. Internet of Things (IoT)
7. Visual technology
8. Simulation and modelling
9. Cloud Technology
10. Blockchain

The suggestions made for DTs to use in easing the integration of remanufacturing will be taken into consideration in the discussion of this thesis but since this part of the second answering where not heavily focused on the technology part but rather the scores given to the factors, these lists will not be analysed further in this section.

Table 14: Digital technologies suggested by case companies for supply uncertainties.

Uncertainty source	**Uncertainty**	**A**	**B**	**C**	**D**	**E**	**F**
Supply	Raw material availability	2	5	2	-	2,4	1
	Supply lead time (schedule adherence)	-	3	4	-	2, 4, 5	1, 2
	Used product availability	3	4, 5, 6	-	-	4, 5, 9	4, 9
	Quality of used product	-	4, 5, 6	8	-	4, 6, 8, 10	1, 7
	Collection procedure	-	-	8	-	1, 4, 5, 9	4, 9
	Transportation lead time	-	4, 8	4, 8	-	1, 4	5, 9
	Variation in the quality level of used product	4	4, 5	4	-	4, 6, 8	1, 2

Table 15: Digital technologies suggested by case companies for process uncertainties.

Uncertainty source	Uncertainty	A	B	C	D	E	F
Process	Yield and quality	4	4, 5	8	-	2, 10	1, 2
	Processing times	3	5	8	-	1, 5	1
	Machine availability	2, 3	-	8	-	4, 5	4
	Labor resoruces	3, 4	5, 8	8	-	1, 3	1
	Change in prodcution	3	-	8	-	1, 2	5, 9
	Lack of competence in remanufacturing	3	3	8	-	1, 2, 3	2, 4, 8

Table 16: Digital technologies suggested by case companies for demand uncertainties.

Uncertainty source	Uncertainty	A	B	C	D	E	F
Demand	Quantity	3	-	4	-	1, 2, 4, 6,9	4, 5, 9
	Product specification	3, 4	-	4	-	7, 8	4, 5
	Change in customer preference	3	-	8	-	2, 9	4
	Market competition	-	-	8	-	4	9,4
	Customer quality requriements	3	-	8	-	4	4,5
	Customer perception (used products vs.new products	3	-	4	-	4, 6, 8, 10	9,8
	Economic downturn	-	-	-	-	-	-

Table 17: Digital technologies suggested by case companies for control uncertainties.

Uncertainty source	Uncertainty	A	B	C	D	E	F
Control	Accuracy of assessing the used product	2	3, 4	4	-	5, 9, 10	-
	Economic feasibility	3	-	8	-	4	4,5
	Forecasting method of returned products	3	3, 4	8	-	4	4, 5
	Lack of control of the original supplier	3	-	4	-	6, 9	5, 9
	Remanufacture planning with the supplier network	3	8, 9	4	-	5, 9, 10	5

5 Discussion

This section aims to address the research questions presented in section 1.3 by discussing the findings from both the literature review and case study in relation to each other. The purpose is to provide a comprehensive analysis of the research questions. As a reminder, the research questions are:

RQ1: *Which digital technologies are suited for remanufacturing in an ETO environment?*

RQ2.1: *Which factors determine the potential of remanufacturing in an ETO environment?*

RQ2.2: *Which supply chain uncertainties must ETO companies face when integrating remanufacturing practices?*

RQ3: *How can digital technologies address the uncertainties associated with the integration of remanufacturing into an ETO supply chain?*

5.1 Digital technologies suited for remanufacturing

This section will try to answer the first research question "Which digital technologies are suited for remanufacturing in an ETO environment?".

Remanufacturing in an ETO environment presents unique challenges and opportunities. To effectively implement remanufacturing practices in this context, DTs play a crucial role. Several DTs have been identified in the literature as well-suited for remanufacturing in an ETO environment, these are presented in Table 18. These technologies offer numerous benefits and have the potential to transform the remanufacturing process.

Table 18: Overview and description of digital technologies for remanufacturing in an ETO environment.

No.	Tech.group	References
1	Automation and industrial robots	[1], [2], [3], [6], [7]
2	Additive manufacturing	[1], [2], [3], [4], [6], [7]
3	Cyber-physical systems (CPS)	[1], [5]
4	Data analytics	[1], [2], [3], [4], [5], [6], [7]
5	Integration of IT systems	[2], [3]
6	Internet of Things (IoT)	[1], [2], [3], [4], [5], [6], [7]
7	Visual technology	[1], [2], [3], [4], [6], [7]
8	Simulation and modelling	[1], [3], [6], [7]
9	Cloud Technology	[1], [2], [3], [5], [7]
10	Blockchain	[1], [6]
[1]: Zheng et al. 2021 [2]: J. Strandhagen et al. 2019 [3]: Rüßmann et al. 2015 [4] Jo Wessel Strandhagen et al. 2022 [5]: Sousa Jabbour et al. 2018 [6]: Kerin and Pham 2019 [7]: Sullivan et al. 2020		

One DT that holds significant promise for remanufacturing in an ETO environment is CPS. CPS can be used to monitor ship performance in real-time and carry out environmental monitoring (Mellbye, Rialland et al. 2016). The integration of CPS technology in smart and connected ships enables seamless communication between various onboard systems, sensors, and devices, enhancing vessel performance, safety, and operational efficiency (Shenoi et al. 2015). In an ETO environment, CPS can provide real-time data on the condition and performance of remanufactured components, allowing for proactive maintenance and optimization of operations (Zheng et al. 2021).

The IoT is another DT that holds great potential for remanufacturing in an ETO environment. By collecting and transmitting real-time data from various sensors and devices, IoT enables remote monitoring, condition-based maintenance, and optimization of vessel performance and energy efficiency (Shenoi et al. 2015). In the context of remanufacturing, IoT can facilitate the collection of valuable data on the history and usage of remanufactured components, enabling accurate assessment of their quality and facilitating their integration into the product life cycle (Antikainen et al. 2018).

Data analytics, powered by big data analytics tools, can also play a crucial role in remanufacturing in an ETO environment. By analyzing large quantities of data generated through sensors and real-time monitoring, data analytics can provide insights that support decision-making, improve operational efficiency, and enable risk assessment (Mirović et al. 2018; Shenoi et al. 2015). In the context of remanufacturing, data analytics can help identify patterns and trends in the performance of remanufactured components, aiding in quality control and process optimization.

Cloud technology offers significant advantages for remanufacturing in an ETO environment by enabling the effective use of resources internationally and facilitating greater product mobility (Shenoi et al. 2015). The adoption of cloud computing technology provides reliable information and immediate processing for all actors in the supply chain, creating a collaborative environment for cross-border e-maritime services (Dellios and Papanikas 2014). In an ETO environment, cloud technology can facilitate the sharing of data and information between different stakeholders involved in the remanufacturing process, enhancing coordination and efficiency.

Blockchain technology, with its distributed nature, immutability, and smart contract capabilities, holds great potential for enhancing information sharing, efficiency, transparency, and trust among stakeholders in the maritime industry (Pu and Lam 2021). In an ETO environment, blockchain technology can be utilized to ensure the traceability and authenticity of remanufactured components, enabling better control over the product life cycle and fostering trust between customers and suppliers.

Implementing DTs in an ETO environment for remanufacturing presents both opportunities and challenges. While these technologies offer significant benefits, it is important to critically evaluate their suitability and consider potential obstacles. Challenges such as customization complexity, process variability, infrastructure investment, and compatibility between different technologies need to be addressed. However, despite these challenges, the integration of DTs can optimize design and planning phases, enable data-driven decision-making, enhance remanufacturing efficiency through automation and robotics, and ultimately improve the effectiveness and sustainability of the remanufacturing process in an ETO context.

5.2 Factors that determine the potential for remanufacturing

This section will examine the findings of the case study and attempt to interpret the meaning behind the scores assigned to various factors based on information gathered from interviews with the case companies. The discussion aims to address research question 2.1: "Which factors determine the potential of remanufacturing in an ETO environment?".

Table 16 presents the 16 factors that received a score higher than the average threshold of 3 in terms of relevance. These factors will be dsicussed in the upcoming paragraphs, with a focus on average scores and variation in the scores given by the case companies will be highlighted.

Table 19: Relevant factor that determine the potential for remanufacturing

Categories	**Factors**	**A**	**B**	**C**	**D**	**E**	**F**	**AVG**
Product condition	Level of damage	4	5	4	2	5	4	4
	Level of fatigue	4	5	5	4	5	5	4.67
Technical specification	Material value	2	4	5	3	2	3	3.17
	Product documentation	1	2	4	4	4	4	3.17
	Type of product	5	5	5	2	4	1	3.67
	Technical lifetime	5	3	3	3	3	4	3.5
	Innovation rate	5	3	3	3	3	2	3.17
External factor	Regulations	2	4	5	4	4	5	4
Product cost	Cost of operations new product vs. used	5	5	5	5	3	3	4.33
	Cost difference new product vs. used product	2	5	5	5	3	3	3.83
Product structure	Standard components	2	4	3	4	3	4	3.33
	Transferability	2	4	4	3	3	4	3.33
	Technical complexity	2	3	4	4	3	3	3.17
Product performance	Quality	5	4	3	5	3	4	4
	Fuel efficiency	5	3	4	4	4	2	3.67
	Operational efficiency	4	3	4	4	4	3	3.67

The top five factors identified by the companies were the level of damage and fatigue, regulations, cost of operations for a used product vs. a new one, and the quality of the used product. These factors are of an intuitive nature and align with the findings from existing literature. However, there are some companies that deviate from the majority opinion.

While the product condition, including the level of damage and fatigue, has an overall consensus among the companies Company D has scored the level of damage as a 2. One can argue that this deviating score given by Company D is due to the company not having to answer to a customer when it comes to their remanufacturing. While they heavily rely on remanufacturing internally, their products are not sold to external customers. While the company still has to follow industry regulations, the strict requirements imposed by external customers on remanufactured products do not apply to Company D.

Another interesting observation from Table 19 is the scores given by the two shipyard companies for fuel efficiency and operational efficiency. While most companies rated these factors as 4 or 5, the shipyard companies gave them lower scores. During the company interviews the different guarantees that the companies had to their customers were highlighted. The shipyards, being the companies providing guarantees ranging from none to one year, had different perspectives on these factors. For Company B the ownership of the marine vessels they provide their customers are not within their ownership when the vessel is delivered to the customer, and due to the lack of control of operations, the company had a guarantee of 1 year. On the other hand, Company F, a shipyard heavily involved in circular strategies, is unable to provide guarantees for remanufactured vessels due to the high risk associated with using used products. The companies also highlighted that whenever new products are introduced they have a guarantee on these products, but most of the time the guarantee is provided through the maritime equipment suppliers. The shipyards' lower scores for these factors can be attributed to the fact that they do not directly bear the consequences when fuel efficiency and operational efficiency are affected by remanufactured products or components.

While both the scored factors and the interview findings indicate a general consensus on the importance of cost of operations and cost differences between remanufactured and new products, Company F ranked relatively lower than other case companies. It can be suggested that the reason for the low rating of the product cost factors is the numerous instances of successful remanufacturing projects observed by Company F. During the interview, the company highlighted that they could estimate a total cost of remanufacturing of 10-15% compared to building a new vessel from scratch. This is an interesting observation considering their extensive experience in building new vessels, which allows them to make a direct comparison. Company A also scored the cost of a product lower than other companies but gave a score of 5 for the cost of operations. This can be attributed to the fact that Company A specializes in delivering thruster and propulsion systems to maritime vessels, and cost of operations, along with fuel efficiency (which they also scored 5), are important factors to stay competitive in the market.

Product documentation was another factor mentioned by the case companies in relation to remanufacturing. This includes maintenance records, certificates, running time, and component records. Companies C, D, E, and F emphasized the importance of product documentation. Company E, a classification society, highlighted the need to ensure that remanufactured products meet the same safety standards as new ones. They emphasized the necessity of detailed information regarding the original construction of the products and components, applicable requirements, and whether third-party verification was conducted during the manufacturing process. Additionally, the company mentioned that the product operation history, including maintenance records, is crucial for remanufacturing.

Additionally, they stressed the significance of product operation history and maintenance records, which are required by regulations and available in the onboard maintenance systems of ships. Company F mentioned that without proper documentation, they cannot determine the keel laying date of a boat, and if the equipment does not possess the required certification for that specific year, it cannot be used. This becomes especially crucial when considering remanufacturing with used items. Company F shared an example of a used product without proper documentation that could not be used, despite being in excellent condition with only 20 hours of running time. The company also noted that products made today are essentially the same, with the only difference being the documentation being up-to-date, compared to products manufactured before the 2000s. However, due to the lack of required documentation for recertification, the product was deemed unsuitable for remanufacturing.

The type of product was also deemed highly influential in determining the potential for remanufacturing. Companies A, B, and C all assigned a score of 5 to this factor, indicating its crucial role in the decision-making process. These companies mentioned that remanufacturing steel structures is easier compared to electric products and components, which have experienced rapid innovation in recent decades. Company A specifically mentioned that their thruster and propulsion systems, which are submerged in seawater during operations, pose additional challenges for remanufacturing due to corrosion and wear and tear over extended periods of use.

A noteworthy finding regarding this factor is the scores assigned by the two companies with extensive experience in remanufacturing. Company D gave a score of 2, while Company F gave a score of 1, indicating that they consider this factor to be less relevant or not relevant at all. Both companies emphasized the challenges associated with reusing and remanufacturing electric components. The case companies also mentioned the difficulty with reusing and remanufacturing products that er directly related to risk and safety on board. The two case companies emphasized that attempting to remanufacture these types of products had little benefit due to the stringent requirements imposed by classification companies. Company E, further mentioned that during a study of their collaborative partners, they found that the type of products that had greater potential for remanufacturing are those that offer safety guarantees, economic viability, and reliable access to spare parts. Examples that were mentioned were steel structures as promising components for remanufacturing.

Company A, a maritime equipment company, distinguishes itself from other case companies in terms of its scores on three factors within the product structure category. While the other case companies assigned scores of either 3 or 4 for the factors of standard components, transferability, and technical complexity, Company A assigned these factors a score of 2. Although the precise reasons for this differentiation are not explicitly stated in the case interview with Company A, one can argue that their products' high level of complexity, coupled with their experience in handling customized products that are permanently welded onto vessels, accounts for this distinction. Despite manufacturing their customized products using standardized components, the company possesses extensive experience in managing customized products and maintains a flexible production system capable of accommodating variations, including ETO products and the unique nature of remanufacturing used products.

While existing literature covers certain aspects related to product-level considerations, much of the previous research on this topic takes a holistic approach. As found in the literature study, Sundin 2004 identified the ease of access, ease of identification, wear resistance, and ease of handling as the most frequently important properties. Sundin 2004 findings align with the findings from this case study which emphasize the importance of product documentation for identification, wear resistance through the technical lifetime, level of damage and fatigue, and ease of handling are highlighted through standard components, type of products and technical complexity. Ziout et al. 2014 holistic approach to the decision-making for EOL products recovery options presented many factors, but also some on the product level which is within the scope of this thesis. The proposed factors such as standard components and the value of a used product compared to a new one are factors that align with the findings of this case study.

The considerations made by N. Nasr and Thurston 2006 align with the decision-making and assessment processes conducted by the case companies when determining the potential for remanufacturing used products. Specifically, the factors examined by N. Nasr and Thurston 2006 that align with the case companies' considerations include the innovation rate of product components, which particularly impacted products with electronic components, as well as the value and cost of the components, and the condition of the used product.

5.3 Uncertainties that remanufacturing bring

Introducing remanufactured products into an ETO supply chain presents uncertainties and challenges that must be carefully managed. This section will try to answer RQ2.2, "Which supply chain uncertainties must ETO companies face when integrating remanufacturing practices?", by utilizing knowledge found in literature, Section 2, and experiences shared from the case companies in Section 4.

ETO companies, which prioritize customisation and cater to customer-specific requirements, face the challenge of handling returned used products when integrating remanufacturing. This introduces additional complexity to the supply chain (Goodall et al. 2015). The lack of information flow between the product use phase and the remanufacturer can create uncertainties, which need to be addressed to ease the integration of remanufacturing practices.

5.3.1 Supply uncertainties

ETO companies in the maritime industry integrating remanufacturing practices must address several supply uncertainties. These include raw material availability, supply lead time, used product availability, quality of used product, collection procedure, and transportation lead time. These factors align with the findings from the literature study in section 2.1.1.

Another significant uncertainty is the availability of used products for remanufacturing. Companies A, B, D, and F have all mentioned the challenge of finding an adequate supply of used products. In the case of Company B, which focuses on ship remanufacturing, the scarcity of used ships is a specific concern. While many shipping companies express interest in purchasing used vessels for remanufacturing purposes, identifying sellers proves to be a challenge. Unlike centralized platforms in consumer markets like eBay, the maritime industry lacks an established marketplace for buying and selling ships, making it difficult to connect buyers with sellers. Improving access to available ships and facilitating connections between buyers and sellers could enhance the supply of used products for remanufacturing.

The quality of used products is another major uncertainty. All companies (A, B, C, D, and F) identified the quality of used products as a significant concern. There is variation in the condition of returned components, and ensuring compatibility with remanufacturing processes is crucial. Preliminary assessments are necessary to determine which components can be utilized, which ones cannot be used, and which ones need to be discarded. Parts compatibility is also highlighted, as outdated or incompatible components can render remanufacturing infeasible. The overall quality of the remanufactured products depends on the availability of used products that meet the required quality standards.

The collection procedure for used products presents additional challenges. Companies A, B, and D mentioned the difficulties associated with collecting used vessels. Unlike platforms where cars can be gathered from various brokers, the fragmented nature of ship sales requires potential buyers to contact multiple brokers individually. This lack of a centralized platform complicates the collection process and increases lead time. Similarly, the transportation lead time of used products is highlighted by Company F as a challenge. Shipping large and heavy used products, such as cranes, can be a complex and time-consuming process, particularly when transporting them from distant locations.

5.3.2 Process uncertainties

The literature reveals the complex and diverse nature of processes in the supply chain which has integrated circular strategies such as remanufacturing. This integration can lead to variations in yield and quality, processing times, equipment availability, and labour resources (Goltsos et al. 2019). The findings from the multiple case study align with the findings from the literature, and the following paragraphs will highlight this.

Company B and F highlight the uniqueness of each remanufacturing project, due to the wide range of products used and their varying conditions. The literature findings state that "Companies operating with an ETO supply chain, referred to as ETO companies, are businesses specializing in creating highly customized products produced on low volumes, which can lead to one-of-a-kind production scenarios tailored to specific customer requirements" (Gosling and M. M. Naim 2009; Powell et al. 2014; Wikner and Rudberg 2005; Olhager 2003). Given the information presented, it is reasonable to argue that ETO companies are particularly well-suited for the integration of remanufacturing. These companies possess the knowledge and experience necessary to handle unique projects and one-of-a-kind production scenarios. Their specialization in creating highly customized products in low volumes aligns closely with the challenges and requirements of remanufacturing. With their expertise in tailoring production to specific customer needs, ETO companies are likely to possess the necessary skills, processes, and adaptability to effectively implement remanufacturing strategies. Company F said it well in the interviews by highlighting that the ETO production is not serial production of standard components and further emphasizes that the company remanufactures with what is available of used products. This indicates the ETO company is used to flexible production and large variations in production.

Labour resources were repetitively mentioned during the case study as an uncertainty often regarded when talking about introducing remanufacturing. The argument often is that the employees must have wide and experienced knowledge of how to handle one-of-a-kind products and remanufacturing situations. ETO production is characterized by the requirement for highly skilled labour due to the complex and customized nature of the products (Powell et al. 2014). Whilst these characteristics for ETO production do not consider the knowledge of remanufacturing and its process, ETO companies have a good starting point when it comes to the workforce already employed in these companies. While Company B indicates that the work required for remanufacturing varies from project to project can lead to uncertainties in the workforce as to who should perform which tasks.

Due to this variation in tasks, Company B furthers the need for labour resources with both wide diversity and experience with handling remanufacturing processes. Company A was fairly confident in the integration of remanufacturing processes in their current workforce due to the highly skilled workers and the experience these workers had with handling difficult and challenging manufacturing tasks. The availability of skilled personnel who possesses the necessary expertise in remanufacturing becomes crucial for executing these activities not only for the production workers but as highlighted by Company F the sales representatives and buyers of used products as well. The lack of such competence can affect the quality of the final remanufactured product and increase the risk of human errors throughout the remanufacture supply chain.

5.3.3 Demand uncertainties

Understanding the uncertainties is especially important for the source demand for ETO companies because this type of manufacturing is customer-centric.

Demand uncertainties are an interesting one. Company C mentions that the remanufacturing market is not established in the maritime industry, and therefore the demand for such products can be difficult to imagine. Furthermore, Company A emphasized that the uncertainties regarding customer preferences, quality requirements and quantity are factors that are difficult to predict. These uncertainties align with the findings from the literature study where Goltsos et al. 2019 emphasized examples being customer preferences and uncertainty in quantity demanded.

Another aspect to consider in ETO companies is the specialized nature of their products and services, which can contribute to demand uncertainties for remanufactured products. As company B emphasized that the demand for new construction tends to be more appealing than remanufactured in the maritime industry. The company highlighted that this was not because the remanufactured product is dated, but due to the fact that the remanufactured product is customized and adapted to the activity it is supposed to do 100%. These statements align with the literature findings regarding customer preference and the challenges associated with ensuring that remanufactured vessels meet the customer's requirement.

Another important aspect of ETO companies which also is notable for demand uncertainties is the specialized areas these products and services operate. Such products and services are usually not flexible and modular to fit other market segments than the one it is designed for, and therefore arguably being a type of product that can benefit from the use of remanufacturing to follow the market demand. In the findings from the literature economic downturn was an uncertainty Goltsos et al. 2019 presented for remanufacturing practices. This aligns with the findings from the case interview where Company F mentioned that when oil prices go down the demand for recycling vessels goes up as well as remanufacturing of ships for other maritime segments such as fishery. Examples to highlight from the case study are the shipyards that were interviewed, Companies B and F, both had experience with remanufacturing offshore vessels to become fishing vessels in periods where macroeconomic factors such as oil prices were low.

Another interesting challenge with the ETO supply chain is the importance of customers. This type of manufacturing is customer centered making customer perception and requirements to lifetime and quality heavily weighted when a company decides whether to integrate remanufacturing or not. An example to highlight from the case study is that Company C is only driven to remanufacture if there are specific customers that initiate the interest of remanufacturing products originally made and provided by Company C. Whilst Company F has managed to integrate such a practice so heavily into their operations that it can account for 50% of the company's present operations. Understanding the quality and technical lifetime of the remanufactured products are crucial for customers to consider remanufacturing, Company B mentioned that these requirements should meet the same requirements as new products do for customers to even consider choosing to remanufacture over new products. Here Company F mentioned that the customers that come to them for remanufacturing are not operating in The North Sea and have lower standards and requirements for the remanufactured products than what customers operating in The North Sea do.

While Company D, a shipping company, stated that customer perception was not as relevant to their operations, it remained an uncertainty for other companies. The acceptance of remanufactured products compared to new ones varies among customers. Overcoming any negative perceptions regarding remanufactured products and promoting their value and sustainability benefits is crucial for successful implementation.

Market competition heavily relies on the existence of requirements and regulations governing the remanufacturing of used products. For companies aiming to remanufacture products that were not originally manufactured by them, the process becomes considerably challenging. Success in such cases depends on factors such as the type of product, applicable regulations, and the availability of product documentation. As noted by Company C, customer preference plays a significant role, as customers generally prefer the original manufacturer to handle the remanufacturing of used products.

5.3.4 Control uncertainties

Companies that currently have remanufacturing practices integrated into their operations, such as Company D and Company F, have provided valuable insights into the uncertainties related to control aspects in the supply chain. On the other hand, companies without prior remanufacturing experience found it more challenging to grasp the uncertainties that arise in terms of control.

One significant uncertainty in integrating remanufacturing activities is the control over accurately assessing the condition and compatibility of used products. Several case companies, including B, C, D, and F, have highlighted this challenge. Major deviations in the assessment of the product will have consequences on the company's ability to control the supply chain as well as these factors will affect the manufacturing process. Since control uncertainties often occur from the attempts to manage the uncertainties originating from supply, process and demand (Mason-Jones and Towill 1997) Control uncertainties can arise when variations in assessment lead to variations in process uncertainties such as a change in production, processing times and lack of competence in remanufacturing.

Company F has identified the uncertainty of underestimating the extent of a project, leading to longer-than-expected processing times and delivery times. This occurs when the complexity and scope of the project are not accurately assessed in the initial phase, causing delays in the overall process. Accurately assessing the used product is crucial to avoid such delays. Similarly, Company C emphasizes the importance of aligning production and ordering materials to avoid delays, highlighting the uncertainties associated with accurately assessing the required work for remanufacturing.

Determining the economic feasibility of remanufacturing introduces uncertainties related to pricing strategies and cost considerations. Company C emphasizes the challenges of establishing appropriate pricing for remanufactured products, especially when relying solely on hourly rates. They recognize the potential for suppliers to benefit more by intentionally prolonging the remanufacturing process to earn more. On the other hand, Company B adopts a hybrid contract solution with fixed prices and additional hourly rates to mitigate this uncertainty. Accurately predicting the extent of the remanufacturing job is crucial for fair pricing. It can be argued that Company C is more susceptible to challenges related to pricing strategies and extended supplier timelines since the company has outsourced their manufacturing activities.

The lack of control over original suppliers of remanufactured products introduces uncertainties in the supply chain. The long life cycles of marine products and vessels contribute to uncertainties in sourcing the original suppliers of used products suitable for remanufacturing. Company D, which has extensive experience in sourcing used goods from certified scrapyards, has encountered issues with sourcing the original manufacturer of used products. Missing product documents or the original manufacturer no longer existing due to mergers, bankruptcies, or other factors add to the uncertainties in obtaining necessary parts, information, and materials for remanufacturing. This can cause delays and result in higher costs.

Planning remanufacturing activities within the supplier network introduces uncertainties related to coordination and communication. Company C, for example, experiences this challenge due to their production activities being outsourced to other suppliers. Company D has also faced communication issues when sourcing original manufacturers of products. Reluctance from the original suppliers to provide necessary information further compounds the uncertainty. Effective coordination and communication within the supplier network are essential to address this uncertainty.

Forecasting demand in a constantly changing market poses a challenge for Company F. They rely on their expertise and in-depth market knowledge to speculate on demand. While they may not know the specific buyers, they are confident that someone will be interested in acquiring the remanufactured product. However, they also acknowledge the need to continuously monitor the market. As new component production increases and new products meet global demand, the delivery time for new products decreases. This could pose challenges for Company F in selling its inventory of used products and highlights the significance of aligning forecasting to prevent idle products in its inventory. Such variations in forecasting demand, with relying on skilled labour can lead to control uncertainties in the supply chain. Control uncertainties in regards to forecasting demand align with findings from literature where Goltsos et al. 2019 identified this as a control uncertainty for the supply chain with remanufacturing practices.

5.4 Digital technologies to address the uncertainties remanufacture practices brings

Lastly, the final research question will be answered, "How can digital technologies address the uncertainties associated with the integration of remanufacturing into an ETO supply chain?". This section will focus on how DTs can ease the integration of remanufacturing by addressing the uncertainties such practices bring to an ETO supply chain. The following paragraphs will offer insights into specific solutions for the uncertainties identified in the case study. It will draw upon recommendations provided by the case companies and findings from the literature study to propose practical ways in which these technologies can be utilized.

In order for remanufacturing to be economically feasible, two essential uncertainties need to be present: The availability of used products and a marked demand for remanufactured products (Kerin and Pham 2019). Acquiring used products serves as the initial step in establishing the remanufacturing system. How DTs can affect the supply or availability of used products will be first discussed.

Case companies B and F shared this concern and stressed the need for a more streamlined supply of such components. The case study highlighted the absence of a centralized platform for companies interested in purchasing used products, which makes the process of finding maritime equipment or used ships straining. As suggested by the case companies, to address the supply uncertainty, cloud technology can be leveraged to establish a virtual platform that spans worldwide, facilitating the procurement of used components.

This aligns with the use of cloud technology presented by Rüßmann et al. 2015 and Sousa Jabbour et al. 2018, such a platform can be service-based, meaning that customers and suppliers work together to offer and purchase various services such as used goods, but can also include other services such as designing, simulating, manufacturing and assembling products. Implementing such a platform can catalyze a more connected maritime industry and alleviate issues faced by Company B, such as the difficulty of locating available used products in the market due to a lack of visibility on sellers. By establishing a comprehensive platform, access to available used products can be improved, and the process of connecting buyers and sellers can be facilitated. This initiative has the potential to enhance the efficiency of procurement, reduce search costs, and promote collaboration within the maritime industry.

As Goodall et al. 2015 and literature findings mention the high level of uncertainty associated with the returned used product complicates remanufacturing compared to traditional linear manufacturing. Goodall et al. 2015 highlighted the lack of information flow between early life cycle phases and the remanufacturer to be a reason for uncertainty occurring with used products.

Further, the case study revealed that the case companies had a lot of concerns handling the variation in the quality of the returned used products. The variation in quality has been discussed as a source of uncertainty in regard to supply, process and control. In the control uncertainties this was identified as the degree of accuracy of assessing the condition of the sued products. The variation in supply would lead to constant changes in production which can have an effect on the yield and quality of the remanufactured product. These uncertainties pertain to evaluating the quality of the used product and determining the necessary actions for remanufacturing the used product. Company F highlighted the uniqueness of each remanufacturing project due to the wide variation in the used products they employ for ship remanufacturing. As Company C highlighted in their interview this assessment determines which components can be utilized, which ones cannot, and which ones require discarding.

To address the uncertainty regarding the assessment of used products in terms of identifying the remanufacture process and quality checking used products several DTs were recommended. To highlight some suggestions from the case companies, were additive manufacturing, cyber-physical systems, integration of IT systems, blockchain technology, simulations and modelling, Internet of Things and data analytics. The following paragraphs will present some examples of how these technologies can meet the uncertainties regarding variations between the returned used products.

IoT can be used for real-time monitoring of production processes, this involves collecting and analyzing data from sensors on machines to identify potential problems before they cause downtime or quality issues (Zheng et al. 2021). As IoT has the potential to link suppliers and customers digitally, it can assist in the procurement of used products (Kerin and Pham 2019). The increase in connectivity achievable with IoT devices, combined with cloud technology such as a centralized platform as previously suggested could transform the remanufacturing maritime industry by enabling remote monitoring, condition-based maintenance on remanufactured products, asset tracking, and optimization of vessel performance (Shenoi et al. 2015). The high level of data collecting can be used in other technologies such as data analytics, machine learning, creating CPS, and performing simulation and modelling.

Product history has been a recurring topic for the case companies where several issues regarding the collection of such data have been highlighted. Company A stated in their interviews that identifying the history of products is a problem. Antikainen et al. 2018 and Kerin and Pham 2019 suggested the use of simulations in the form of digital twins as a solution. As Okumus et al. 2023 states "By almost removing uncertainty about the state of returned end-of-life cores, digital twins may play a crucial role in supporting rapid decision-making and planning in used component acquisition." Digital twins can therefore be used to estimate the remaining usable life of products based on data received from IoT for product and component functionality (Okumus et al. 2023). The predictive model has the capability to anticipate the future condition of both the complete product and its components during the initial project phase, enabling the estimation of the price of remanufacturing services and identifying production processes that the remanufacturing must include. Such a predictive model can help control uncertainties of both pricing and assessment of the used product, enabling effective planning and accurate quality control.

The amount of information feedback throughout a product's useful life will also significantly affect the uncertainty at the remanufacturing stage (Okumus et al. 2023). Findings from the case study highlighted maintenance records, third-party verification and certificates, as well as the maintenance system Company F highlighted many sources of data which can be collected and analyzed to understand the condition of the ship and its equipment. These data collections are in regular contact with the product, through service and scheduled maintenance, and enable data to be recorded throughout the product use phase. Using sensors and IoT can enable monitoring during the use phase of its life cycle, thus allowing for real-time diagnostics (Okumus et al. 2023). This data can through big data analytics improve quality control by recognizing patterns and trends that may indicate quality issues (Rüßmann et al. 2015) Which can enable remanufacturers to know the condition of the product prior to its arrival for remanufacture, reducing areas within the quality of the used product and enabling production processes to be planned ahead of time and therefore reducing the remanufacturing time and potential errors.

Blockchain technology has the potential to address some of the challenges associated with the supply of used goods from uncertified scrapyards in South Asia and the Middle East. By leveraging blockchain, manufacturers and other stakeholders can establish a secure and transparent supply chain management system (Pu and Lam 2021). One of the key advantages of blockchain is its ability to provide a decentralized and immutable ledger that records all transactions and activities related to a particular product. This means that every step in the supply chain, from the initial raw material extraction to the final remanufactured product, can be traced and verified (Zheng et al. 2021). This transparency enables manufacturers to have a clear understanding of the product's history, including its source, ownership, and any intermediate processes it has undergone. By having access to such comprehensive data, manufacturers can better assess the quality and condition of the used goods sourced from scrapyards. One can utilize this information to make well-informed choices regarding the suppliers they choose to collaborate with, thereby minimizing the risks involved in purchasing from unreliable sources. This is particularly important for Company F as they have encountered instances where the quality of products differed from what the seller had claimed.

Furthermore, blockchain technology can facilitate the implementation of smart contracts and automated verification processes. Smart contracts are self-executing agreements that trigger predefined actions once certain conditions are met. For instance, a smart contract could be designed to release payment to the scrapyards only after the products have been assessed and verified as meeting the required standards. This reduces the reliance on manual verification processes and enhances the efficiency and accuracy of quality assessments. Overall, the utilization of blockchain technology in the supply chain management of used goods can provide manufacturers with increased visibility, trust, and control over their sourcing processes. By leveraging the secure and transparent nature of blockchain, manufacturers can make more informed decisions, enhance the accuracy of product assessments, and ultimately reduce the risks associated with purchasing from uncertified scrapyards.

As the interviews reflect demand forecasting plays a crucial role in the maritime ETO supply chain, especially in the constantly changing market such as the maritime. Company F, in particular, faces challenges in accurately predicting demand and aligning their forecasting to prevent used products and components from remaining idle in their inventory. Today, Company F rely their forecasting on their expertise and in-depth market knowledge to speculate on demand patterns. To address these uncertainties with forecasting when integrating remanufacturing practices the most recommended technology by the case companies was data analytics.

By analyzing historical sales data, market trends, and other relevant factors, Company F can gain valuable insights into demand patterns and make informed decisions regarding inventory management. Data analytics can transform data into knowledge and action within a manufacturing system (J. Strandhagen et al. 2019), this also includes a remanufacturing one. By identifying seasonal fluctuation, emerging trends, and potential shifts in customer preference, data analytics and big data can enable the company to adjust their procurement and remanufacturing practices accordingly. This also includes monitoring the oil and gas prices to make a prediction as to if the prices are stable or shifting.

The production of maritime ETO products involves a wide variety of products (Bertrand and Muntslag 1993; Jo Wessel Strandhagen et al. 2022). This requires a high level of coordination and collaboration between the wide network of stakeholders in the supply chain. Outsourcing production activities to other suppliers, as experienced by Company C, introduces additional uncertainties related to coordination and communication within the remanufacturing process. Planning and managing remanufacturing activities within a supplier network require effective coordination and communication channels to mitigate potential disruptions and delays. The case companies suggested multiple DTs when planning remanufacturing activities with supplier network, some of these included integration of IT systems and cloud technology. Integration of IT systems and cloud technology can facilitate seamless communication and information sharing among stakeholders, enabling better coordination between suppliers and minimizing delays. The integration of IT systems in both horizontal and vertical dimensions fosters a higher level of cohesion among companies, departments, functions, and capabilities, enabling seamless data sharing and collaboration (Rüßmann et al. 2015). Such IT systems can include ERP, MES or PLM (Jo Wessel Strandhagen et al. 2022).

The production process in a maritime supply chain is characterized by a high level of labour intensity, as it involves a wide variety of skilled labour and is typically non-repetitive (Bertrand and Muntslag 1993; Jo Wessel Strandhagen et al. 2022; Powell et al. 2014; J.

Strandhagen et al. 2019), this aligns with the findings from the case study where companies B, D and F emphasized the need for a wide diversity in expertise, due to the large variations and unique character that each remanufacturing project has. The availability of skilled personnel becomes crucial for executing these activities efficiently. Company F stressed that such expertise comes from years of experience. The case companies suggested automation and industrial robots, cyber-physical systems, data analytics, integration of IT systems and simulation and modelling for handling uncertainties tied to labour resources. Some of the technologies will be highlighted in the following paragraphs.

Automation and industrial robots have the potential to revolutionize the remanufacturing processes in the maritime industry. While Company B stressed that the tasks involved in remanufacturing can vary from ship to ship, automation can be leveraged to streamline repetitive or physically demanding tasks (Zheng et al. 2021; Jo Wessel Strandhagen 2022). Industrial robots can be programmed to perform specific operations with precision, reducing the need for manual labour and enhancing overall efficiency. By automating certain aspects of the remanufacturing process, companies can allocate skilled labour resources to more complex and critical tasks, thereby optimizing their expertise and improving productivity.

Simulation and modelling are vital tools for understanding and optimizing labour resource allocation in the maritime engineer-to-order supply chain and can be utilized to enhance the production process (Zheng et al. 2021). By creating virtual representations of the remanufacturing processes, companies can simulate different scenarios, assess resource requirements, and optimize labour allocation (Rüßmann et al. 2015). Such simulations can be used in the preliminary project that Company C highlighted to be required for remanufacturing to be efficient.

While not highlighted by the case companies, findings from the literature highlight the use of visual technologies in the form of VR and AR to contribute to labour resources. Through AR, computer-generated 3D images of the real world, creating a VR can construct a visual representation of an object (J. Strandhagen et al. 2019), including a used product. The AR in manufacturing can be used for maintenance, by overlaying computer-generated information so technicians can identify issues and make repairs (Zheng et al. 2021). AR and VR technologies can provide immersive training experiences, allowing workers to acquire and enhance their skills in a virtual environment. These technologies enable hands-on practice and simulations, replicating real-world remanufacturing scenarios and enhancing the expertise of the labour force.

In summary, the integration of remanufacturing into an ETO supply chain poses uncertainties that can be mitigated by DTs. Cloud technology can establish a virtual platform for procuring used components, enhancing supply certainty. Technologies like IoT, data analytics, and simulation modeling can address uncertainties in assessing product quality, enabling effective planning and accurate quality control. Blockchain can provide a secure and transparent supply chain management system, reducing risks associated with sourcing from uncertified scrapyards. Data analytics can improve demand forecasting and coordination within the supply chain. Finally, automation, simulation modeling, and AR/VR technologies can optimize labor resource management. These digital solutions offer practical ways to ease uncertainties and enhance efficiency in the remanufacturing process.

6 Conclusion

In conclusion, this thesis has explored the integration of remanufacturing practices within an ETO supply chain in the maritime industry. Through a mixed-method approach involving a literature study and a multiple case study analysis of various stakeholders, significant findings and valuable insights have been uncovered.

Firstly, the research has identified 16 key factors that play a crucial role in determining the potential for remanufacturing at the product level. These factors provide valuable guidance for companies seeking to incorporate remanufacturing strategies into their operations, allowing them to assess the viability of remanufacturing within their specific contexts.

Secondly, the study has highlighted the uncertainties that arise when integrating remanufacturing into an ETO supply chain. These uncertainties stem from various sources, including supply, process, demand, and control. By understanding these uncertainties, companies can proactively address and manage them, thus enhancing the effectiveness of their remanufacturing initiatives.

Furthermore, this research has emphasized the role of DTs in addressing the uncertainties associated with remanufacturing integration. By harnessing the power of DTs, such as data analytics, IoT, simulation and modelling, and cloud technology, companies can mitigate risks, enhance visibility, and optimize decision-making processes within their remanufacturing operations.

Going forward, future research should focus on understanding which uncertainties are specific for each stakeholder and should be explored by only focusing a case study on one stakeholder from the maritime industry. The adoption of remanufacturing in the maritime industry depends on the clear economic benefits of operations and the product itself, which was demonstrated through the case study. How ETO companies can benefit from remanufacturing instead of new construction needs to be shown through further case studies of remanufacturing used products.

The success stories of certain companies can serve as motivation for other companies facing challenges in envisioning large-scale remanufacturing in the maritime industry. It is essential to address the obstacles that stakeholders encounter due to existing regulations in order to enable such a transition. The integration of positive incentives to promote the adoption of circular strategies and the utilization of remanufactured items is crucial for the industry to transition to a CE. Policymakers should consider implementing measures such as tax breaks and schemes to encourage the utilization of remanufactured items. A comprehensive study that maps the current regulatory barriers and their impacts on hindering the integration of remanufacturing on a large scale is necessary to demonstrate the benefits to governmental bodies and policymakers.

By addressing these research questions and shedding light on the potential of DTs, factors influencing remanufacturing, and supply chain uncertainties, this thesis contributes to the growing body of knowledge on sustainable practices within the maritime industry. It is hoped that the insights gained from this study will inspire and motivate companies to embrace remanufacturing as a means to achieve sustainability and economic prosperity in the sector.

6.1 Limitations

It is important to acknowledge the limitations of this study. The level of expertise among the case companies in integrating remanufacturing varied, which can impact the interpretation of the findings. Certain companies had extensive experience and shared valuable insights acquired over the years, while others were less experienced, potentially leading to more speculative viewpoints.

Additionally, the case study suffered from an uneven distribution of stakeholders. Some stakeholders were represented by multiple companies, while others were represented by only one. This imbalance may affect the weighting of the results and discussions, as certain stakeholders possess greater representation than others.

Bibliography

Adrodegari, Federico et al. (2015). 'Engineer-to-order (ETO) production planning and control: an empirical framework for machinery-building companies'. In: *Production Planning & Control* 26.11, pp. 910–932.

Alcaide, Juan Ignacio, Emilio Rodrıguez-Dıaz and Francisco Piniella (2017). 'European policies on ship recycling: A stakeholder survey'. In: *Marine Policy* 81, pp. 262–272.

Aldrighetti, Riccardo et al. (2022). 'The performance impact of Industry 4.0 technologies on closed-loop supply chains: insights from an Italy based survey'. In: *International Journal of Production Research* 0.0, pp. 1–26.

Ali, Faheem et al. (2015). 'Remanufacturing as a sustainable strategy in shipbuilding industry: A case study on Norwegian shipyards'. In: *Advances in Production Management Systems: Innovative Production Management Towards Sustainable Growth: IFIP WG 5.7 International Conference, APMS 2015, Tokyo, Japan, September 7-9, 2015, Proceedings, Part II 0*. Springer, pp. 232–239.

Allwood, Julian M et al. (2011). 'Material efficiency: A white paper'. In: *Resources, conservation and recycling* 55.3, pp. 362–381.

Alqahtani, Ammar Y, Surendra M Gupta and Kenichi Nakashima (2019). 'Warranty and maintenance analysis of sensor embedded products using internet of things in industry 4.0'. In: *International Journal of Production Economics* 208, pp. 483–499.

Ang, Joo Hock et al. (2017). 'Energy-efficient through-life smart design, manufacturing and operation of ships in an industry 4.0 environment'. In: *Energies* 10.5, p. 610.

Antikainen, Maria, Teuvo Uusitalo and Päivi Kivikytö-Reponen (2018). 'Digitalisation as an Enabler of Circular Economy'. In: *Procedia CIRP* 73. 10th CIRP Conference on Industrial Product-Service Systems, IPS2 2018, 29-31 May 2018, Linköping, Sweden, pp. 45–49. ISSN: 2212-8271. DOI: https://doi.org/10.1016/j.procir.2018.04.027. URL: https://www.sciencedirect.com/science/article/pii/S2212827118305432.

Battini, Daria, Marija Bogataj and Alok Choudhary (2017). *Closed loop supply chain (CLSC): economics, modelling, management and control.*

Bauer, Tom et al. (2020). 'Characterization of circular strategies to better design circular industrial systems'. In: *Journal of Remanufacturing* 10, pp. 161–176.

Benbasat, Izak, David K Goldstein and Melissa Mead (1987). 'The case research strategy in studies of information systems'. In: *MIS quarterly*, pp. 369–386.

Bertrand, J Will M and Dennis R Muntslag (1993). 'Production control in engineer-to-order firms'. In: *International Journal of Production Economics* 30, pp. 3–22.

Bhatia, Manjot Singh et al. (2022). 'What's critical for closed-loop supply chain operations? - Findings from the Indian small and medium manufacturing enterprises'. In: *Journal of Cleaner Production* 372.

Blomsma, Fenna (2018). 'Collective 'action recipes' in a circular economy–On waste and resource management frameworks and their role in collective change'. In: *Journal of Cleaner Production* 199, pp. 969–982.

Blomsma, Fenna and Geraldine Brennan (2017). 'The emergence of circular economy: a new framing around prolonging resource productivity'. In: *Journal of industrial ecology* 21.3, pp. 603–614.

Bocken, Nancy MP et al. (2016). 'Product design and business model strategies for a circular economy'. In: *Journal of industrial and production engineering* 33.5, pp. 308–320.

Boehme, Tillmann (2009). 'Supply Chain Integration: A Case-based Investigation of Status, Barriers, and Paths to Enhancement.' PhD thesis. The University of Waikato.

Bressanelli, Gianmarco et al. (2018). 'Exploring how usage-focused business models enable circular economy through digital technologies'. In: *Sustainability* 10.3, p. 639.

Bucy, Michael et al. (2016). 'The 'how'of transformation'. In.

Cannas, Violetta G and Jonathan Gosling (2021). 'A decade of engineering-to-order (2010–2020): Progress and emerging themes'. In: *International Journal of Production Economics* 241, p. 108274.

Cannas, Violetta G, Jonathan Gosling et al. (2019). 'Engineering and production decoupling configurations: an empirical study in the machinery industry'. In: *International journal of production economics* 216, pp. 173–189.

Charter, Martin and Casper Gray (Jan. 2008). 'Remanufacturing and product design'. In: *International Journal of Product Development - Int J Prod Dev* 6. DOI: 10.1504/IJPD.2008.020406.

Christopher, Martin (1992). *Logistics & supply chain management*. Pearson Uk.

Circuleire (2023). *What is The Circular Economy?* URL: https://circuleire.ie/the-circular-economy/#what-is-the-ce (visited on 4th May 2023).

Commission, The European (2020a). *Circular economy action plan*. URL: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (visited on 30th Oct. 2022).

— (2020b). *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives*. URL: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32008L0098 (visited on 30th Oct. 2022).

Croom, Simon (2010). 'Introduction to research methodology in operations management'. In: *Researching operations management*. Routledge, pp. 56–97.

Da Silva, Vander Luiz et al. (2020). 'Implementation of Industry 4.0 concept in companies: Empirical evidences'. In: *International Journal of Computer Integrated Manufacturing* 33.4, pp. 325–342.

Da Xu, Li, Wu He and Shancang Li (2014). 'Internet of things in industries: A survey'. In: *IEEE Transactions on industrial informatics* 10.4, pp. 2233–2243.

Dalenogare, Lucas Santos et al. (2018). 'The expected contribution of Industry 4.0 technologies for industrial performance'. In: *International Journal of Production Economics* 204, pp. 383–394.

Daniel, Laurent and Sunhye Lee (2022). 'Shipbuilding policy and market developments in selected economies 2022'. In: 131. DOI: https://doi.org/https://doi.org/10.1787/f3faeb3d-en. URL: https://www.oecd-ilibrary.org/content/paper/f3faeb3d-en.

Davis, Tom (1993). 'Effective supply chain management'. In: *Sloan management review* 34, pp. 35–35.

Dellios, Kleanthis and Dimitrios Papanikas (2014). 'Deploying a maritime cloud'. In: *IT Professional* 16.5, pp. 56–61.

Denscombe, Martyn (2017). *EBOOK: The good research guide: For small-scale social research projects*. McGraw-Hill Education (UK).

Eisenhardt, Kathleen M (1989). 'Building theories from case study research'. In: *Academy of management review* 14.4, pp. 532–550.

Farooque, Muhammad et al. (2019). 'Circular supply chain management: A definition and structured literature review'. In: *Journal of cleaner production* 228, pp. 882–900.

Fraser, Matthew, Laxmi Haigh and Alvaro Conde Soria (2023). 'The Circularity Gap Report 2023'. In.

Fulconis, François and Raphael Lissillour (2021). 'Toward a behavioral approach of international shipping: a study of the inter-organisational dynamics of maritime safety'. In: *Journal of Shipping and Trade* 6, pp. 1–23.

Glass, Rupert et al. (2018). 'Identifying the barriers to Industrie 4.0'. In: *Procedia Cirp* 72, pp. 985–988.

Goltsos, Thanos E et al. (2019). 'The boomerang returns? Accounting for the impact of uncertainties on the dynamics of remanufacturing systems'. In: *International Journal of Production Research* 57.23, pp. 7361–7394.

Goodall, Paul, Emma Rosamond and Jenifer Harding (2015). 'A review of the state of the art in tools and techniques used to evaluate remanufacturing feasibility'. In: *Journal of Cleaner Production* 81, pp. 1–15. DOI: 10.1016/j.jclepro.2014.09.091. URL: https://www.sciencedirect.com/science/article/pii/S0959652614006015.

Gosling, Jonathan, Mohamed Naim and Denis Towill (2013). 'Identifying and categorizing the sources of uncertainty in construction supply chains'. In: *Journal of Construction Engineering and Management* 139.1, pp. 102–110.

Gosling, Jonathan and Mohamed M. Naim (2009). 'Engineer-to-order supply chain management: A literature review and research agenda'. In: *International Journal of Production Economics* 122.2, pp. 741–754.

Greener, Sue (2008). *Business research methods*. BookBoon.

Gubbi, Jayavardhana et al. (2013). 'Internet of Things (IoT): A vision, architectural elements, and future directions'. In: *Future generation computer systems* 29.7, pp. 1645–1660.

Hicks, Christian, Tom McGovern and Chris F Earl (2000). 'Supply chain management: A strategic issue in engineer to order manufacturing'. In: *International journal of production economics* 65.2, pp. 179–190.

Hicks, Christian, Tom Mcgovern and Christopher Earl (Apr. 2001). 'A Typology of UK Engineer-to-Order Companies'. In: *International Journal of Logistics Research and Applications* 4. DOI: 10.1080/13675560110038068.

Hiremath, Anand M et al. (2014). ‘Ecological engineering, industrial ecology and eco-industrial networking aspects of ship recycling sector in India’. In: *APCBEE procedia* 10, pp. 159–163.

Hossain, Maruf Md M, Mohammad Mahmudul Islam et al. (2006). *Ship breaking activities and its impact on the coastal zone of Chittagong, Bangladesh: Towards sustainable management*. Advocacy & Publication Unit, Young Power in Social Action (YPSA) Chittagong ...

Initiative, Circularity Gap Reporting et al. (2021). ‘Circularity gap report 2021’. In.

International Association of Classification Societies (IACS) (2022). *Classification Societies - What, Why and How?* Tech. rep. International Association of Classification Societies (IACS). URL: https://iacs.org.uk/media/8871/classification-what-why-how.pdf.

ISO/TC 323 Circular economy (n.d.). https://www.iso.org/committee/7203984.html. Accessed: 2023-03-07.

Jabbour, Charbel Jose Chiappetta et al. (2019). ‘Unlocking the circular economy through new business models based on large-scale data: an integrative framework and research agenda’. In: *Technological Forecasting and Social Change* 144, pp. 546–552.

Jakobsen, Erik W (2011). ‘Norsk maritim verdiskapning 2009’. In: *Retrieved September* 9, p. 2015.

Jansson, Kim (2016). ‘Circular Economy in Shipbuilding and Marine Networks – A Focus on Remanufacturing in Ship Repair’. In: pp. 661–671.

Jünge, Gabriele Hofinger (2022). ‘Lean Engineering Design: Applying Lean Thinking to Engineer-To-Order (ETO) Operations’. In.

Kagermann, Henning et al. (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group*. Forschungsunion.

Karlsson, Christer (2010). ‘Researching operations management’. In: *Researching operations management*. Routledge, pp. 20–55.

Kerin, Mairi and Duc Truong Pham (2019). ‘A review of emerging industry 4.0 technologies in remanufacturing’. In: *Journal of cleaner production* 237, p. 117805.

Kirchherr, Julian, Denise Reike and Marko Hekkert (2017). ‘Conceptualizing the circular economy: An analysis of 114 definitions’. In: *Resources, conservation and recycling* 127, pp. 221–232.

Kok, L, G Wurpel and A Ten Wolde (2013). ‘Unleashing the power of the circular economy’. In.

Kothari, C.R (1993). *Research Methodology, Methods and Techniques*.

Kristoffersen, Eivind (2021). ‘Towards a Smart Circular Economy: How digital technologies can support the adoption of circular economy’. In.

Kristoffersen, Eivind et al. (2020). ‘The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies’. In: *Journal of Business Research* 120, pp. 241–261. ISSN: 0148-2963. DOI: https://doi.org/10.1016/j.jbusres.2020.07.044. URL: https://www.sciencedirect.com/science/article/pii/S0148296320304987.

Kvadsheim, Nina, Deodat Mwesiumo and Jan Emblemsvåg (Aug. 2019). 'Examining Circular Economy Business Models for Engineer-to-Order Products'. In: pp. 570–578. ISBN: 978-3-030-29999-6. DOI: 10.1007/978-3-030-30000-5_70.

Lacy, Peter et al. (2015). 'The product life-extension business model: Products that are built to last'. In: *Waste to Wealth: The Circular Economy Advantage*, pp. 68–83.

Lahrour, Yahya, Daniel Brissaud and Peggy Zwolinski (2019). 'The strategy for implementing remanufacturing process in a commercial enterprise, the case study of a French company'. In: *Procedia CIRP* 80, pp. 554–559.

Lee, Taehee and Hyunjeong Nam (2017). 'A study on green shipping in major countries: in the view of shipyards, shipping companies, ports, and policies'. In: *The Asian Journal of Shipping and Logistics* 33.4, pp. 253–262.

Lincoln, Yvonna S and Egon G Guba (1985). *Naturalistic inquiry*. sage.

Linder, Marcus and Mats Williander (2017). 'Circular business model innovation: inherent uncertainties'. In: *Business strategy and the environment* 26.2, pp. 182–196.

Lund, Robert T and William M Hauser (2010). 'Remanufacturing-an American perspective'. In.

MacArthur, Ellen et al. (2013). 'Towards the circular economy'. In: *Journal of Industrial Ecology* 2.1, pp. 23–44.

MacArthur, Ellen and Dominic Waughray (2016). 'Intelligent Assets: Unlocking the circular economy potential'. In: *Ellen MacArthur Foundation: Cowes, UK*.

Marsh, Alastair T.M., Anne P.M. Velenturf and Susan A. Bernal (2022). 'Circular Economy strategies for concrete: implementation and integration'. In: *Journal of Cleaner Production* 362, p. 132486. ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2022.132486. URL: https://www.sciencedirect.com/science/article/pii/S095965262202087X.

Mason-Jones, Rachel and Denis R Towill (1997). 'Information enrichment: designing the supply chain for competitive advantage'. In: *Supply Chain Management: An International Journal*.

McDonough, William and Michael Braungart (2010). *Cradle to cradle: Remaking the way we make things*. North point press.

Mellbye, Christian Svane, Agathe Rialland et al. (2016). 'Maritim næring i det 21. århundret-Prognoser, trender og drivkrefter'. In: *Menon Economics*.

Mellbye, Christian Svane, MARCUS G Theie and ERIK W Jakobsen (2015). 'Norwegian Maritime Equipment Suppliers 2015'. In: *Federation of Norwegian Industries Oslo*.

Mello, Mario Henrique, Jonathan Gosling et al. (2017). 'Improving coordination in an engineer-to-order supply chain using a soft systems approach'. In: *Production Planning & Control* 28.2, pp. 89–107.

Mello, Mario Henrique and Jan Ola Strandhagen (2011). 'Supply chain management in the shipbuilding industry: challenges and perspectives'. In: *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 225.3, pp. 261–270.

Mikelis, Nikos (2006). 'Developments and issues on recycling of ships'. In: *The East Asian Seas Congress, Haikou City, Hainan Province, PR China*, pp. 12–16.

Milios, Leonidas et al. (2019). ‘Sailing towards a circular economy: Conditions for increased reuse and remanufacturing in the Scandinavian maritime sector’. In: *Journal of Cleaner Production* 225, pp. 227–235.

Mirović, Maris, Mario Miličević and Ines Obradović (2018). ‘Big data in the maritime industry’. In: *NAŠE MORE: znanstveni časopis za more i pomorstvo* 65.1, pp. 56–62.

Morseletto, Piero (2020). ‘Targets for a circular economy’. In: *Resources, Conservation and Recycling* 153, p. 104553.

Nam, SeungHoon et al. (2018). ‘SCP-Matrix based shipyard APS design: Application to long-term production plan’. In: *International Journal of Naval Architecture and Ocean Engineering* 10.6, pp. 741–761.

Nasr, Nabil and Michael Thurston (2006). ‘Remanufacturing: A key enabler to sustainable product systems’. In: *Rochester Institute of Technology* 23, pp. 14–17.

Okumus, Dogancan et al. (2023). ‘Towards a circular maritime industry: Identifying strategy and technology solutions’. In: *Journal of Cleaner Production* 382, p. 134935. ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2022.134935. URL: https://www.sciencedirect.com/science/article/pii/S0959652622045085.

Olhager, Jan (2003). ‘Strategic positioning of the order penetration point’. In: *International journal of production economics* 85.3, pp. 319–329.

— (2010). ‘The role of the customer order decoupling point in production and supply chain management’. In: *Computers in industry* 61.9, pp. 863–868.

Pagoropoulos, Aris, Daniela CA Pigosso and Tim C McAloone (2017). ‘The emergent role of digital technologies in the Circular Economy: A review’. In: *Procedia cirp* 64, pp. 19–24.

Para-González, Lorena, Carlos Mascaraque-Ramırez and Clara Cubillas-Para (2020). ‘Maximizing performance through CSR: The mediator role of the CSR principles in the shipbuilding industry’. In: *Corporate Social Responsibility and Environmental Management* 27.6, pp. 2804–2815.

Parida, Vinit, David Sjödin and Wiebke Reim (2019). *Reviewing literature on digitalization, business model innovation, and sustainable industry: Past achievements and future promises.*

Parker, David et al. (2015). ‘Remanufacturing market study’. In.

Peck, Helen and Uta Juttner (2002). ‘Risk management in the supply chain’. In: *Logistics & Transport Focus* 4.10, pp. 17–22.

POR, European Project (2014-2020). *Closed Loop Supply Chain.* Accessed: 5-3-2019.

Porter, Keith et al. (Aug. 1999). ‘Manufacturing classifications: relationships with production control systems’. In: *Integrated Manufacturing Systems* 10, pp. 189–199. DOI: 10.1108/09576069910280431.

Potting, José et al. (2017). ‘Circular economy: measuring innovation in the product chain’. In: *Planbureau voor de Leefomgeving* 2544.

Powell, Daryl et al. (2014). ‘A New Set of Principles for Pursuing the Lean Ideal in Engineer-to-order Manufacturers’. In: *Procedia CIRP* 17. Variety Management in Manufacturing, pp. 571–576.

Pu, Shuyi and Jasmine Siu Lee Lam (2021). 'Blockchain adoptions in the maritime industry: a conceptual framework'. In: *Maritime Policy & Management* 48.6, pp. 777–794.

Raj, Alok et al. (2020). 'Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective'. In: *International Journal of Production Economics* 224, p. 107546.

Reichel, Almut et al. (2016). 'Circular economy in Europe: Developing the knowledge base'. In: *European Environment Agency Report* 2, p. 2016.

Reid, Robert and Nada R. Sanders (2019). *Operations Management*. 7th. Hoboken, NJ: Wiley. ISBN: 978-1-119-45782-0.

Russell, Jennifer D and Nabil Z Nasr (2023). 'Value-retained vs. impacts avoided: the differentiated contributions of remanufacturing, refurbishment, repair, and reuse within a circular economy'. In: *Journal of Remanufacturing* 13.1, pp. 25–51.

Rüßmann, Michael et al. (2015). 'Industry 4.0: The future of productivity and growth in manufacturing industries'. In: *Boston consulting group* 9.1, pp. 54–89.

Sanchez Rodrigues, Vasco et al. (2008). 'Establishing a transport operation focused uncertainty model for the supply chain'. In: *International Journal of Physical Distribution & Logistics Management* 38.5, pp. 388–411.

Schroeder, Greyce N et al. (2016). 'Digital twin data modeling with automationml and a communication methodology for data exchange'. In: *IFAC-PapersOnLine* 49.30, pp. 12–17.

Shenoi, RA et al. (2015). 'Global marine technology trends 2030'. In.

Shipbuilding (WP6), The OECD Council Working Party on (2010). *OECD Council Working Party on Shipbuilding (WP6) ENVIRONMENTAL AND CLIMATE CHANGE ISSUES IN THE SHIPBUILDING INDUSTRY*. URL: https://www.oecd.org/sti/ind/46370308.pdf (visited on 4th May 2023).

Simonetto, Marco et al. (2022). 'Closed loop supply chains 4.0: From risks to benefits through advanced technologies. A literature review and research agenda'. In: *International Journal of Production Economics* 253, p. 108582.

Sjøbakk, Børge, Maria Kollberg Thomassen and Erlend Alfnes (2014). 'Implications of automation in engineer-to-order production: a case study'. In: *Advances in Manufacturing* 2.2, pp. 141–149.

Sousa Jabbour, Ana de et al. (Nov. 2018). 'Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations'. In: *Annals of Operations Research* 270.

Stahel, Walter (2010). *The performance economy*. Springer.

— (Mar. 2016). 'Circular economy'. In: *Nature* 531, pp. 435–438. DOI: 10.1038/531435a.

Stankovic, Mirjana et al. (2017). 'Industry 4.0: Opportunities behind the challenge'. In: *Background Paper for UNIDO General Conference*. Vol. 17, pp. 2017–11.

Strandhagen, Jo et al. (Aug. 2019). 'Digitalized Manufacturing Logistics in Engineer-to-Order Operations'. In: pp. 579–587. ISBN: 978-3-030-29999-6. DOI: 10.1007/978-3-030-30000-5_71.

Strandhagen, Jo W et al. (2018). ‘Operationalizing lean principles for lead time reduction in engineer-to-order (ETO) operations: A case study’. In: *IFAC-PapersOnLine* 51.11, pp. 128–133.

Strandhagen, Jo Wessel (2022). ‘Towards Next-Generation Yard Logistics’. In.

Strandhagen, Jo Wessel et al. (2022). ‘Sustainability challenges and how Industry 4.0 technologies can address them: a case study of a shipbuilding supply chain’. In: *Production Planning & Control* 33.9-10, pp. 995–1010.

Sullivan, Brendan P et al. (2020). ‘Maritime 4.0–opportunities in digitalization and advanced manufacturing for vessel development’. In: *Procedia manufacturing* 42, pp. 246–253.

Sundin, Erik (2004). ‘Product and process design for successful remanufacturing’. PhD thesis. Linköping University Electronic Press.

Tobro, Runa Lunde (2017). ‘Applicability of Lean and Value Stream Mapping Techniques in Turbulent High-Variety, Low-Volume Manufacturing Environments’. In.

Tonelli, Marcello and Nicoló Cristoni (2018). *Strategic management and the circular economy*. Routledge.

Tozanlı, Özden, Elif Kongar and Surendra M Gupta (2020). ‘Evaluation of waste electronic product trade-in strategies in predictive twin disassembly systems in the era of blockchain’. In: *Sustainability* 12.13, p. 5416.

Van Der Vorst, Jack GAJ and Adrie JM Beulens (2002). ‘Identifying sources of uncertainty to generate supply chain redesign strategies’. In: *International Journal of Physical Distribution & Logistics Management*.

Voss, Chris (2010). ‘Case research in operations management’. In: *Researching operations management*. Routledge, pp. 176–209.

Wahab, D.A. et al. (2018). ‘A review on the applicability of remanufacturing in extending the life cycle of marine or offshore components and structures’. In: *Ocean Engineering* 169, pp. 125–133. ISSN: 0029-8018. DOI: https://doi.org/10.1016/j.oceaneng.2018.08.046. URL: https://www.sciencedirect.com/science/article/pii/S002980181831638X.

Wikner, Joakim and Martin Rudberg (2005). ‘Integrating production and engineering perspectives on the customer order decoupling point’. In: *International journal of operations & production management* 25.7, pp. 623–641.

Willner, Olga et al. (Aug. 2015). ‘Exploring the Archetypes of Engineer-to-order: An Empirical Analysis’. In: *INTERNATIONAL JOURNAL OF OPERATIONS PRODUCTION MANAGEMENT* 1, pp. 1–42. DOI: 10.1108/IJOPM-07-2014-0339.

Winans, Kiara, Alissa Kendall and Hui Deng (2017). ‘The history and current applications of the circular economy concept’. In: *Renewable and Sustainable Energy Reviews* 68, pp. 825–833.

Xu, Xun et al. (2021). ‘Industry 4.0 and Industry 5.0—Inception, conception and perception’. In: *Journal of Manufacturing Systems* 61, pp. 530–535. ISSN: 0278-6125. DOI: https://doi.org/10.1016/j.jmsy.2021.10.006. URL: https://www.sciencedirect.com/science/article/pii/S0278612521002119.

Yin, Robert K (2009). *Case study research: Design and methods*. Vol. 5. sage.

Zeballos, Luis J. et al. (2012). 'Addressing the uncertain quality and quantity of returns in closed-loop supply chains'. In: *Computers Chemical Engineering* 47. FOCAPO 2012, pp. 237–247. ISSN: 0098-1354. DOI: https://doi.org/10.1016/j.compchemeng.2012.06.034. URL: https://www.sciencedirect.com/science/article/pii/S0098135412002189.

Zheng, Ting et al. (2021). 'The applications of Industry 4.0 technologies in manufacturing context: a systematic literature review'. In: *International Journal of Production Research* 59.6, pp. 1922–1954.

Ziout, A, A Azab and M Atwan (2014). 'A holistic approach for decision on selection of end-of-life products recovery options'. In: *Journal of cleaner production* 65, pp. 497–516.

Zuidema, Remko H (2015). 'Open building as the basis for circular economy buildings'. In: *Proceedings of the Future of Open Building Conference*. ETH Zürich.

Appendix

A Interviewguide used in case study

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

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1. Information about the company

- Which type of products do you see as fit for implementing circular activities in?
- Annual volume of the company (quantity per year)?
    - 1-10
    - 11-100
    - 101-1000
    - 1001-10,000
    - >10,000
- Duration (weeks per project)?
    - 1-10
    - 11-50
    - 51-100
    - >100
- Cost per unit? (Thousands euro)
    - 1-10
    - 11-100
    - 101-1000
    - 1001-10,000
    - >10,000
- Engineering hours (hours pr project)?
    - 0-100
    - 101-1000
    - 1001-10,000
    - >10,000

2. Questions about the supply chain

- To what degree does the company operate with circular economy activities?
    - Reuse
    - Repair
    - Refurbishment/Remanufacturing
    - Reuse
- What have been the barriers/challenges when adapting the operations to circular economy activities?
    - If not, what has been stopping the company from initializing this?
    - 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 is the company most likely to adapt to?
    - Reuse
    - Repair
    - Remanufacturing and refurbishment
    - Recycle
- What circular activities have the largest potential to give economic benefits to the company?
- What are the financial implications of implementing circular economy activities, and how do you mitigate these risks?

3. Uncertainties in a supply chain operating with remanufacturing

- What are the main uncertainties that you face in your supply chain when implementing refurbishment/remanufacturing?
- How do you manage the uncertainties associated with the quality of returned products?
- How do you balance the demand for new products and remanufactured products, and what are the factors that influence this decision?

4. Remanufacturing/refurbishment

- What does remanufacturing mean for the company?
- What does refurbishment mean for the company?
- How do you define remanufacturing and refurbishment?
- How is remanufacturing/refurbishment integrated into your engineer-to-order supply chain?
- What are the benefits of remanufacturing compared to other circular economy activities?
    - Such as repair, recycle, reuse
- By adapting will this or has this affected the performance of the company?

- If yes, then why?

5. Digital technologies

- How does the company use digital technology today?
- How have these digital technologies improved your supply chain visibility and transparency?
- How do you use data analytics to manage uncertainties in your supply chain, such as demand forecasting or product quality control?
- How can digital technologies be used to address these uncertainties?
- Which digital technologies can be used to address the uncertainties and which uncertainties do they mitigate?
- What are the benefits of using digital technologies to support circular economy activities in your ETO supply chain?

Relevant information

Circular Economy:

Circular economy is an economic model that aims to keep resources in use for as long as possible, extracting the maximum value from them while minimizing waste and pollution. It is based on three key principles: designing out waste and pollution, keeping products and materials in use, and regenerating natural systems.

To achieve a circular economy, companies can engage in a variety of activities, such as reuse, repair, remanufacturing, refurbishment, recycling.

Reuse: Reuse of discarded yet still usable product, for the same purpose, by a different user.

Repair: Repair and maintenance of broken or malfunctioning product, to enable continuation of its original function.

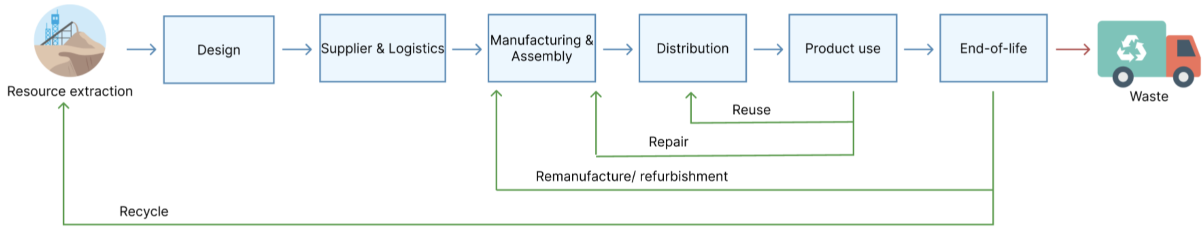
Remanufacturing: Refers to the transformation of used products, consisting of components and parts, into products that satisfy the same quality and standards as new products.

Recycle: Refers to the process of converting waste materials into new reusable materials and objects

There are examples of engineer-to-order companies that have successfully implemented circular economy activities in their supply chain. For example, General Electric (GE), GE has a Remanufacturing

Program that focuses on the repair, refurbishment, and remanufacturing of various components and systems, including aircraft engines, locomotive engines and medical imaging equipment. For both the aircraft engines and the locomotive the process involves disassembling the product, inspecting each component, and replacing worn or damaged parts. The product is reassembled and tested to meet the same standards as a new product.

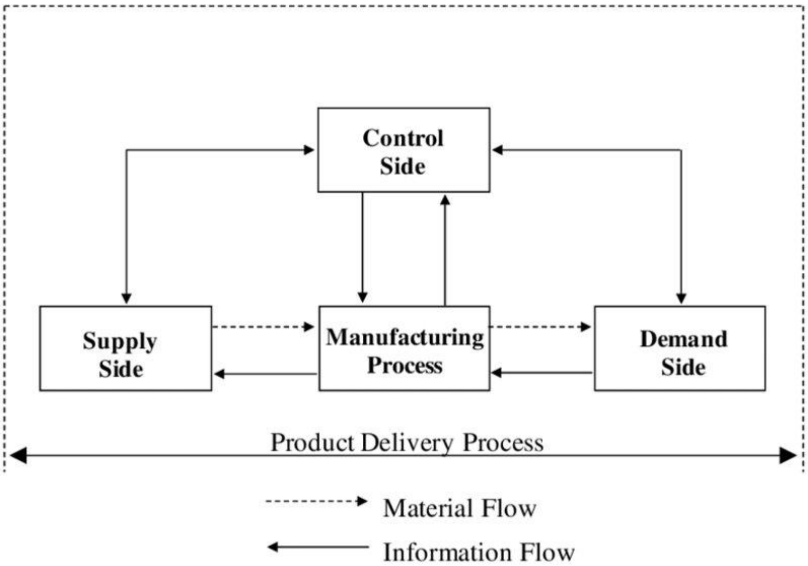
For a general shipbuilding supply chain, the circular activities may look something like:



Supply chain uncertainties

The supply chain uncertainty circle

The supply chain uncertainty circle is a model used to explain the different types of uncertainties that can arise in a supply chain. The model consists of four types of uncertainties that are interdependent and can create a cycle of uncertainty:



Supply uncertainty: Refers to the unpredictability of the availability, quantity, and quality of raw materials, components, and finished goods that are needed to meet customer demand.

Examples: delays in the delivery of critical components or materials, quality issues with parts or equipment

Process uncertainty: Refers to the unpredictability of the manufacturing, distribution, and logistics processes involved in getting products from suppliers to customers.

Examples: equipment breakdown, delays in transportation, unexpected changes in production schedules

Demand uncertainty: This refers to uncertainty in the market demand for a product or service, which can make it difficult to forecast future demand.

Examples: Consumer preferences, market trends

Control uncertainty: Refers to the unpredictability of the internal and external factors that affect a company's ability to manage its supply chain effectively.

Examples: Changes in regulations, political instability, or fluctuations in currency exchange rates

Digital technology

The Industry 4.0 paradigm with its vision for the future digitized factory was introduced in 2011 and has led to a range of technology initiatives to improve manufacturing and operations.

Industry 4.0 represents the fourth industrial revolution after the mechanization, electrification and computerization of production environments (Kagermann, et al., 2013). It focuses on the increasing digitization and automation of the manufacturing industry, especially by means of digital value chains between products, machines and operators.

Industry 4.0 is powered by nine foundational technologies: additive manufacturing, atonomous robots, cloud computing and manufacturing, cybersecurity, cyber-physical systems, data analytics, horizontal and vertical system integration, the Internet of Things, and visual technology.

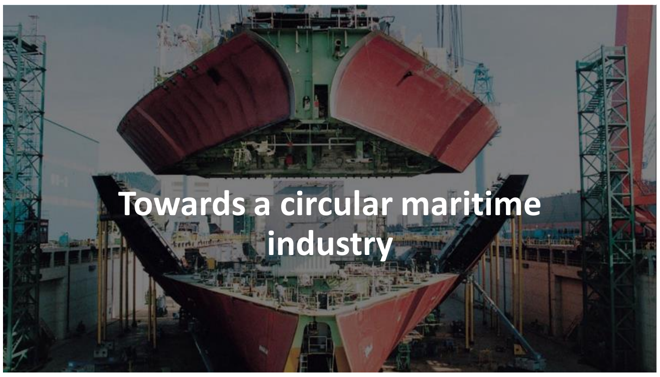
Table 1: Overview of Industry 4.0 technology

Tech. group	Description
Autonomous robots	Autonomous robots' devices are programmed to perform tasks with little to no human intervention or interaction. Autonomous robots can be utilized in a supply chain operation that includes lower-value, potentially dangerous or high-risks tasks. Manufacturing, final assembly, and warehousing are areas where automated robots already have a presence. Autonomous robots can be substitutes for advanced software, simple machines or tools and human workforce. Example of autonomous robots are, Automatic Guided Vehicles (AGVs) Autonomous Mobile Robots (AMRs)

	Collaborative robots (COBOTs) for material handling and performing logistics operations.
Additive manufacturing (AM)	Additive Manufacturing (AM) is an appropriate name to describe the technologies that produce physical 3D objects by adding layer-upon-layer of material, whether the material is plastic, metal, concrete, etc. using computer-based 3D design. There are two main fields of interest: establishing a local supply infrastructure for 3D-printed spare parts in major ports to accelerate delivery and exploiting the unique capabilities of AM technology to make parts no other manufacturing process can produce.
Cloud manufacturing	Cloud computing is the practice of using a network of remote servers hosted on the Internet to store, manage, and process data, rather than a local server or a personal computer. The same principles of shared information are at use with cloud manufacturing. It is a service-oriented business model for sharing and exchange of data between systems, sites and companies on a cloud platform. Manufacturers can utilize cloud manufacturing for product planning, production and stock tracking (with Enterprise Resource Planning (ERP) software), Productivity management to monitor when to change production, these are just some of what cloud manufacturing can be used in a supply chain.
Cyber security	Cybersecurity is part of the information technology term that focuses on protecting electronic assets. I the roam of Industry 4.0, this could be data collections or digital information. Cyber security is the secure and reliable protection of industrial production systems from cyber threats. Types of cyber security: Critical infrastructure security Application security Network security Cloud security Internet of Things (IoT) security
Cyber-physical systems (CPS)	They are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the Internet. Enables automation, monitoring, and control of processes and objects in real-time.
Data analytics	The use and collection of operational systems and machine data to find improvements in a process. Real-time information allows for enhanced decision-making and process improvements, as well as insight into troubleshooting assessment and predictive maintenance

	Data analytics allow for real time insights, process improvements, predicitive maintenance ++. Big data, Machine learning, AI (Artificial Intelligence), advanced simulations, digital twin
Integration of IT systems	Horizontal integration of IT systems in industry 4.0 are connected networks of cyber-physical and enterprise systems. Vertical integration in the industry 4.0 of roam aims to tie together all logical layers within the organization through all layers of the organizational structure and supply chain. Horizontal and vertical integration of IT systems examples Enterprise Resource Planning (ERP), Product Lifecycle Management systems and Manufacturing Execution Systems (MES)
Industrial Internet of Things (IIoT)	IIoT (Industrial Internet of Things) is a subcategory of IoT (Internet of Things) used in an industrial context. It's a unique phenomenon where various digital tools are used to connect data and machines in factories and throughout the supply chain for productivity and quality. These sensors and actuators enable storing and exchange of information through network technology. (IoT describes the network of physical objects embedded with software, sensors, and other technologies to connect and exchange data with systems and devices over the internet.) Can be used in combination with several of the other technologies listed to name some; data analytics, visual technology, digital twin, CPS, ++
Visual technology	The visual representation of an object, in the form of augmented reality (AR), through superimposing a computer-generated 3D image in the real world, creating a virtual reality (VR) or projecting 3D images as holograms. Application areas: Visualization interacts with environment, warehouse management Operation and control, assembly ++

B Presentation guide used during case study interviews



Goal of the conversation

- Map today's initiatives aimed at moving towards a circular economy
- Identify the circular economy activities with the greatest potential in the shipbuilding industry
- Identify which factors that determine greatest potential for ETO products
- Determine the uncertainties that implementing circular economy activities may bring to a shipbuilding supply chain
- Develop strategies to how technology can mitigate those uncertainties

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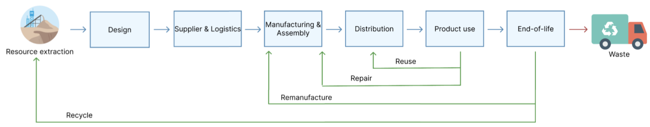
Circular economy in the shipbuilding industry

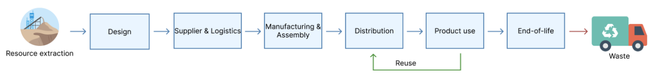


"The implementation of CE logic will replace production with sufficiency; reuse what you can, recycle what cannot be reused, repair what is broken, and remanufacture what cannot be repaired".

(Stahel, 2016)

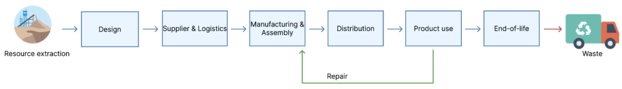
Reuse

Reuse of discarded yet still usable product, for the same purpose, by a different user.



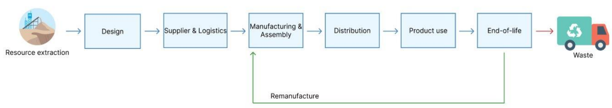
Repair

Repair and maintenance of broken or malfunctioning product, to enable continuation of its original function.



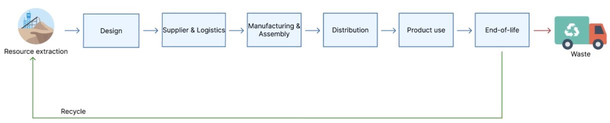
Remanufacture

Refers to the rebuilding of a product to the specifications of a new product using a combination of reused, repaired and virgin materials.



Recycle

Refers to the process of converting waste materials into new reusable materials and objects



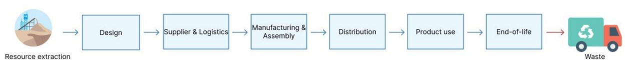
Information about the company

- Type of products?
- Annual volume of the company? (quantity per year)
  - 1-10
  - 11-100
  - 101-1000
  - 1001-10,000
  - >10,000
- Duration? (weeks per project)
  - 1-10
  - 11-50
  - 51-100
  - >100

- Cost per unit? (Thousands euro)
  - 1-10
  - 11-100
  - 101-1000
  - 1001-10,000
  - >10,000
- Engineering hours? (hours per project)
  - 0-100
  - 101-1000
  - 1001-10,000
  - >10,000

Questions about the current supply chain

- What CE activities are in operation today?
  - Reuse
  - Repair
  - Remanufacturing
  - Recycle
- Barriers and challenges?
- Which activities have the greatest potential?



Goal of the conversation

- Map today's initiatives aimed at moving towards a circular economy
- Identify the circular economy activities with the greatest potential in the shipbuilding industry
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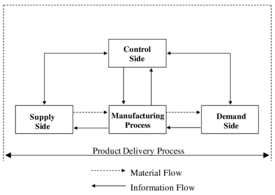
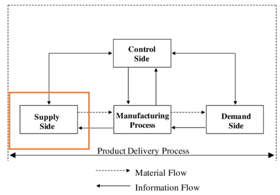
Supply chain uncertainty circle

- Describes the dynamic relationship between different sources of uncertainty in the supply chain
- Will be used as tool to identify and separate the sources of uncertainty



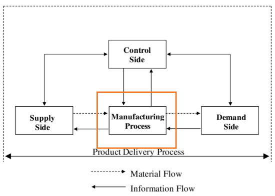
Supply chain uncertainty circle

- **Supply uncertainty:** Refers to the unpredictability of the availability, quantity, and quality of raw materials, components, and finished goods that are needed to meet customer demand.
- Examples: delays in the delivery of critical components or materials, quality issues with parts or equipment



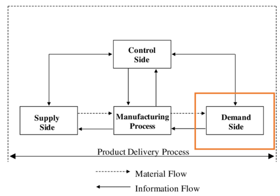
Supply chain uncertainty circle

- **Process uncertainty:** Refers to the unpredictability of the manufacturing, distribution, and logistics processes involved in getting products from suppliers to customers.
- Examples: equipment breakdown, delays in transportation, unexpected changes in production schedules



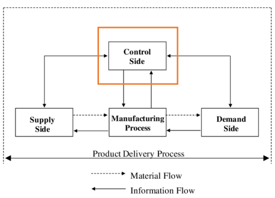
Supply chain uncertainty circle

- **Demand uncertainty:** Refers to the unpredictability of customer demand for products and services.
- Examples: Consumer preferences, market trends



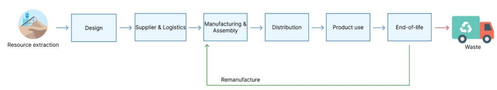
Supply chain uncertainty circle

- **Control uncertainty:** Refers to the unpredictability of the internal and external factors that affect a company's ability to manage its supply chain effectively.
- Examples: Changes in regulations, political instability, or fluctuations in currency exchange rates



Remanufacturing in the shipbuilding industry

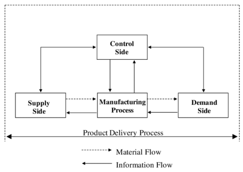
- Remanufacturing to the company
- An integrated part of today's operations?
- Factors that determine the potential for remanufacturing a product/component

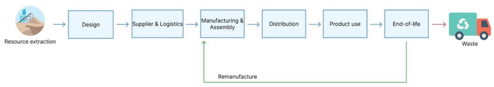


Categories	Factors	Description
Product condition	Level of damage	Extent of rust, corrosion, or other forms of deterioration.
	Level of fatigue	Extent of material fatigue due to wear from operation.
Location of product	Geographical location of product	Distance from product to factory.
	Product placement on vessel	The degree of accessibility for dismantling a product from the vessel is determined by the physical location of the product.
Technical specification	Material composition	Specific types and proportions of materials or substances used in product.
	Material value	Value of material.
	Product documentation	Overview of product history (Maintenance reports, overview of routes).
	Type of product	Mechanical, hydraulic, electric or software.
	Technical lifetime	Duration that the product is deemed to be technically reliable and capable of fulfilling its intended purpose.
	Innovation rate	Technology change rate in the market.
External factors	Established remanufacture process	Established systematic method for handling reverse flow and remanufacturing practices.
	Regulations	Regulations that govern maritime operations (classification society, EU..).
Product cost	Cost of operations new product vs. used	The cost of operating a new product vs. Operating a remanufactured one.
	Cost difference new product vs. Used product	Cost of manufacturing a new product vs. Remanufacture as used one.
	Product/component value	Premium product or low-cost product.
Product structure	Design for disassembly	Design for disassembly and separation.
	Standard components	Interchangeable components.
	Transferability	Extent to which a product meets the necessary compatibility requirements for successful transfer to a different location or system.
	Technical complexity	Degree of intricacy and sophistication of its technical aspects, including component count, interdependencies, and specialized knowledge needed for assembly or maintenance.
Product performance	Quality	Degree to which the product meets requirements and standards.
	Fuel efficiency	New product vs. Used product.
	Operational efficiency	Compatibility with performance range of product.

Uncertainties in a supply chain operating with remanufacturing

- Main uncertainties
  - Supply
  - Process
  - Demand
  - Control
- Uncertainties associated with returned products





Supply uncertainty	- Raw material availability - Supply lead time (schedule adherence) - Used product availability	- Quality of used products - Collection procedure - Transportation lead time - Variation in quality level of used product
Process uncertainty	- Yield and quality - Variation in quality level of used product - Processing times - Machine availability - Batching rules	- Labor resources - Change in productions schedules - Lack of knowledge
Demand Uncertainty	- Quantity - Timing - Locations - Product specification - Customer quality requirement	- Change in customer preferences - Economic downturn - Market competition - Product cannibalization - Customer perception
Control uncertainty	- Stock control policy - Capacity planning decisions - Accuracy of assessment of used product - Economic feasibility of remanufacturing	- Legislation and restrictions - Forecasting method of returned products - Lack of legislation restriction - Lack of control of the processes (used/new) - Supplier network collaboration

Goal of the conversation

- Map today's initiatives aimed at moving towards a circular economy
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- **Develop strategies to how technology can mitigate those uncertainties**

Digital technologies

Tech. group	Description
Autonomous robots and industrial robots	Automatic Guided Vehicles (AGVs), Autonomous Mobile Robots (AMRs), and Collaborative robots (COBOTS) for material handling and performing logistics operations.
Additive manufacturing	3-D printing of objects layer by layer, based on 3-D models or CAD files of the objects.
Cyber-physical systems	Enables automation, monitoring, digital twin and control of processes and objects in real-time.
Data analytics	Transforming data into knowledge and actions within a manufacturing system. Big data for analysis of large sets of real-time data, artificial intelligence, machine learning and advanced simulations are all part of this group.
Integration of IT systems	Horizontal and vertical integration of IT systems for production management (PLM, ERP, MES).
Internet of Things	Objects equipped with sensors and actuators enable storing and exchange of information through network technology.
Visual technology	The visual representation of an object, in the form of augmented reality (AR) through superimposing a computer-generated 3D image in the real world, creating a virtual reality (VR) or projecting 3D images as holograms. (CAD, AR, VR)
Simulations and modelling	Technology that mirror the physical world data such as machines and products. E.g. Digital twin.
Cloud Technology	Cloud manufacturing is a technology that utilizes the internet to establish a virtual and worldwide platform for manufacturing resources and abilities. Cloud-based solutions for sharing and exchange of data between systems, sites, and companies.
Blockchain	Provide a transparent and tamper-proof record of the entire supply chain, from raw material sourcing to product delivery. Enables increased trust, efficiency, and traceability, reducing fraud, ensuring quality control, and facilitating seamless collaboration between different stakeholders.

Digital technologies

- What type of technologies do the company use today?
- Which type of technologies can aid the implementation of remanufacturing?

C Questionnaire used in case study

Enhancing Remanufacturing Potential and Mitigating Uncertainties through Digital Technologies

Date: 22.05.20203

Case company: Company name

This document aims to provide valuable insights into enhancing the potential for remanufacturing and mitigating uncertainties through the adoption of digital technologies. As businesses worldwide increasingly embrace sustainability and circular economy principles, remanufacturing has emerged as a viable solution for reducing waste, conserving resources, and improving operational efficiency.

The document is divided into three sections,

Section 1: Ranking the factors that determine the potential for remanufacturing a used product or component.

Section 2: Providing insights and recommendations on digital technologies that can effectively address uncertainties in remanufacturing supply chains.

Section 3: Open section for additional information.

The highlighted sections indicate where you can provide your responses. At the end of the document, there is an open section where you can share any additional information, if available.

Section 1: Factors Determining Remanufacturing Potential

In this section, we will explore the factors that significantly influence the potential for remanufacturing. The factors listed below are identified through interviewing stakeholders of the maritime industry.

We would like you to rank all factors from 1 to 5, with 5 representing the most critical factors and 1 the least relevant.

Categories	Factors	Description	Range (1-5)
Example X	Factor X	Description X	X

1

Product condition	Level of damage	Extent of rust, corrosion, or other forms of deterioration.	
	Level of fatigue	Extent of material fatigue due to wear from operation.	
Location of product	Geographical location of product	Distance from product to factory.	
	Product placement on vessel	The degree of accessibility for dismantling a product from the vessel is determined by the physical location of the product.	
Technical specification	Material composition	Specific types and proportions of materials or substances used in product.	
	Material value	Value of material.	
	Product documentation	Overview of product history (Maintenance reports, overview of routes).	
	Type of product	Mechanical, hydraulic, electric or software.	
	Technical lifetime	Refers to the duration a product remains to be technically reliable and capable of fulfilling its defined scope of purpose.	
	Innovation rate	Product technology remains current and up to date for multiple product lifecycles	
External factors	Established remanufacture process	An established systematic method for handling reverse flow and remanufacturing activities.	
	Regulations	Regulations that govern maritime operations (classification society, EU..).	
Product cost	Cost of operations new product vs. used	The cost of operating a new product vs. Operating a remanufactured one.	
	Cost difference new product vs. Used product	Cost of manufacturing a new product vs. Remanufacture as used one.	
	Product/component value	Where the product is on the specter from premium to low-cost product	
Product structure	Design for disassembly	Design for disassembly and separation.	
	Standard components	Interchangeable components.	
	Transferability	Extent to which a product meets the necessary compatibility requirements for successful transfer to a different location or system.	

	Technical complexity	Degree of intricacy and sophistication of its technical aspects, including component count, interdependencies, and specialized knowledge needed for assembly or maintenance.	
Product performance	Quality	Degree to which the product meets requirements and standards.	
	Fuel efficiency	New product vs. Used product.	
	Operational efficiency	Compatibility with performance range of product.	

Section 2: Mitigating Uncertainties through Digital Technologies

During our case interviews, we have identified a diverse set of uncertainties that pose significant challenges to the remanufacturing process. This section is meant to offer recommendations on leveraging the digital technologies, listed below, to effectively address and mitigate these uncertainties.

If you find any technologies in the provided list that can address the uncertainties listed in Table 2, kindly provide the corresponding technology number from the "Tech.group" column in Table 3.

Table 2: Uncertainties found when integrating remanufacturing into the supply chain

Uncertainty source	Uncertainty	Description	Examples	Tech. group
Source X	Uncertainty X	Description X		E.g. 1, 2,3
Supply	Raw material availability	Uncertainty regarding the availability of raw materials required for the remanufacturing process.	This could be influenced by factors such as changes in demand, supplier reliability, or disruptions in the supply chain.	
	Supply lead time (schedule adherence)	Uncertainty related to the ability to adhere to the planned schedule for the supply of remanufactured products.	Delays or unpredictability in the supply lead time can impact production planning and customer satisfaction.	
	Used product availability	Uncertainty concerning the availability of an adequate quantity of used products that can be remanufactured.	This could be influenced by factors such as product usage patterns, return rates, or the effectiveness of the collection process.	
	Quality of used product	Uncertainty regarding the condition and quality of the used products returned for remanufacturing.	Variations in the quality of returned products can affect the efficiency and effectiveness of the remanufacturing process.	
	Collection procedure	Uncertainty related to the effectiveness of the collection procedure for used products.	Issues such as low participation rates, logistical challenges, or improper handling can impact the quantity and quality of the products collected for remanufacturing.	

	Transportation lead time	Uncertainty associated with the time required to transport used products from their point of collection to the remanufacturing facility.	Delays or disruptions in transportation can affect the overall efficiency of the remanufacturing process.	
Process	Variation in quality level of used product	Uncertainty regarding the consistency and quality levels of the used products received for remanufacturing.	Wide variations in the quality of returned products can lead to additional complexities in the remanufacturing process and impact the overall quality of the remanufactured products.	
	Yield and quality	Uncertainty regarding the level of yield and quality achieved during the remanufacturing process.	This uncertainty could arise due to variations in the condition of returned products, difficulty in assessing the extent of refurbishment required, and the effectiveness of remanufacturing processes in restoring products to desired quality levels.	
	Processing times	Uncertainty regarding the time required to complete the remanufacturing process for each product.	Factors such as the complexity of the remanufacturing process, variations in product condition, availability of necessary components, and the expertise of the remanufacturing workforce can contribute to variations in processing times.	
	Machine availability	Uncertainty related to the availability and reliability of remanufacturing machines and equipment.	This uncertainty could stem from factors such as machine breakdowns, maintenance requirements, and potential bottlenecks in the remanufacturing process.	
	Labor resources	Uncertainty regarding the availability and skill level of the labor force involved in remanufacturing operations.	The availability of skilled workers trained in remanufacturing processes and their capacity to handle variations in product conditions can influence the overall efficiency and effectiveness of the remanufacturing process.	
	Change in production	Uncertainty associated with managing changes in the production processes and systems when integrating	The introduction of remanufacturing may require adjustments in production lines, inventory management systems, and quality	

		remanufacturing into the existing supply chain.	control processes, leading to potential disruptions and uncertainties.	
	Lack of technology available	Uncertainty resulting from a lack of suitable technology and tools to support remanufacturing operations.	The absence of specialized equipment for remanufacturing processes may obstruct efficiency and quality outcomes.	
	Lack of competence on remanufacturing	Uncertainty stemming from a lack of expertise and knowledge about remanufacturing practices within the supply chain.	This can include limited understanding of remanufacturing concepts, best practices, and the necessary skills and training needed to successfully carry out remanufacturing operations.	
Demand	Quantity	Uncertainty about the quantity of remanufactured products that customers will demand.	It is challenging to predict the exact number of remanufactured products that will be required to meet customer needs and preferences.	
	Product specification	Uncertainty related to the specific features and characteristics customers desire in remanufactured products.	Customers may have varying expectations and preferences for remanufactured products, making it difficult to determine the exact product specifications that will satisfy their needs.	
	Change in customer preference	Uncertainty regarding potential shifts in customer preferences over time.	Customers' preferences for remanufactured products may change due to various factors, such as emerging trends, advancements in technology, or evolving societal attitudes towards sustainability.	
	Market competition	Uncertainty associated with the competitive landscape and the actions of rival companies.	The level of competition in the market for remanufactured products can influence customer demand and affect the integration of remanufacturing into the supply chain.	
	Customer quality requirements	Uncertainty about the level of quality expected by customers for remanufactured products.	Customers may have different quality expectations, and meeting those requirements consistently can pose challenges in remanufacturing operations.	
	Customer perception (used products vs. new products)	Uncertainty regarding how customers perceive, and value remanufactured products compared to new products.	Customer perceptions of remanufactured products, including trust, perceived value, and stigma associated with "used" items, can	

			influence their demand and acceptance in the market.	
Control	Raw material stock control	Uncertainty regarding the availability, quality, and timely procurement of raw materials required for remanufacturing processes.	This includes uncertainties related to sourcing, lead times, and supplier reliability.	
	Accuracy of assessment of used product	Uncertainty in accurately assessing the condition and quality of used products returned for remanufacturing.	This includes uncertainties related to product inspection, testing, and grading processes.	
	Economic feasibility of remanufacturing	Uncertainty regarding the financial viability and profitability of remanufacturing operations.	This includes uncertainties related to cost estimation, pricing, market demand, and competition.	
	Forecasting method of returned products	Uncertainty in accurately predicting the quantity and timing of returned products for remanufacturing.	This includes uncertainties related to customer behavior, market trends, product lifespan, and end-of-life product management.	
	Lack of control of original suppliers	Uncertainty regarding the availability, reliability, and responsiveness of original suppliers of components or parts used in the remanufacturing process.	This includes uncertainties related to supplier relationships, lead times, and potential disruptions in the supply chain.	
	Price policies of used products	Uncertainty regarding the pricing strategies and policies for used products that are being remanufactured.	This includes uncertainties related to market demand, consumer perception, and competitive pricing.	
	Remanufacture planning with supplier network	Uncertainty in effectively planning and coordinating remanufacturing activities with the supplier network.	This includes uncertainties related to capacity planning, production scheduling, logistics coordination, and communication with suppliers.	

Table 3: Digital technology to mitigate the uncertainties found in a supply chain with remanufacturing practices

No.	Tech. group	Description
1	Autonomous robots and industrial robots	Automatic Guided Vehicles (AGVs), Autonomous Mobile Robots (AMRs), and Collaborative robots (COBOTS) for material handling and performing logistics operations.
2	Additive manufacturing	3-D printing of objects layer by layer, based on 3-D models or CAD files of the objects.
3	Cyber-physical systems	Enables automation, monitoring, digital twin and control of processes and objects in real-time.
4	Data analytics	Transforming data into knowledge and actions within a manufacturing system. Big data for analysis of large sets of real-time data, artificial intelligence, machine learning and advanced simulations are all part of this group.
5	Integration of IT systems	Horizontal and vertical integration of IT systems for production management (PLM, ERP, MES).
6	Internet of Things	Objects equipped with sensors and actuators enable storing and exchange of information through network technology.
7	Visual technology	The visual representation of an object, in the form of augmented reality (AR) through superimposing a computer-generated 3D image in the real world, creating a virtual reality (VR) or projecting 3D images as holograms. (CAD, AR, VR)
8	Simulations and modelling	Technology that mirrors the physical world data such as machines and products. E.g. Digital twin.
9	Cloud Technology	Cloud manufacturing is a technology that utilizes the internet to establish a virtual and worldwide platform for manufacturing resources and abilities. Cloud-based solutions for sharing and exchange of data between systems, sites, and companies.
10	Blockchain	Provide a transparent and tamper-proof record of the entire supply chain, from raw material sourcing to product delivery. Enables increased trust, efficiency, and traceability, reducing fraud, ensuring

		quality control, and facilitating seamless collaboration between different stakeholders.

Section 3: Additional information

____

Document end

D Factors ranked by Company A

Table 20: Factors ranked by Company A

Categories	No.	Factors	Description	Range (1-5)
Product condition	1	Level of damage	Extent of rust, corrosion, or other forms of deterioration.	4
	2	Level of fatigue	Extent of material fatigue due to wear from operation.	4
Location of product	3	Geographical location of product	Distance from product to factory.	5
	4	Product placement on vessel	The degree of accessibility for dismantling a product from the vessel is determined by the physical location of the product.	2
Technical specification	5	Material composition	Specific types and proportions of materials or substances used in product.	2
	6	Material value	Value of material.	2
	7	Product documentation	Overview of product history (Maintenance reports, overview of routes).	1
	8	Type of product	Mechanical, hydraulic, electric or software.	5
	9	Technical lifetime	Duration that the product is deemed to be technically reliable and capable of fulfilling its intended purpose.	5
	10	Innovation rate	Technology change rate in the market.	5
External factors	11	Established remanufacture process	Established systematic method for handling reverse flow and remanufacturing practices.	2
	12	Regulations	Regulations that govern maritime operations (classification society, EU..).	2
Product cost	13	Cost of operations new product vs. used	The cost of operating a new product vs. Operating a remanufactured one.	5
	14	Cost difference new product vs. used product	Cost of manufacturing a new product vs. Remanufacture as used one.	2
	15	Product/component value	Premium product or low-cost product.	1
Product structure	16	Design for disassembly	Design for disassembly and separation.	1
	17	Standard components	Interchangeable components.	2
	18	Transferability	Extent to which a product meets the necessary compatibility requirements for successful transfer to a different location or system.	2
	19	Technical complexity	Degree of intricacy and sophistication of its technical aspects, including component count, interdependencies, and specialized knowledge needed for assembly or maintenance.	2
Product performance	20	Quality	Degree to which the product meets requirements and standards.	5
	21	Fuel efficiency	New product vs. Used product.	5
	22	Operational efficiency	Compatibility with a performance range of product.	4

E Factors ranked by Company B

Table 21: Factors ranked by Company B

Categories	No.	Factors	Description	Range (1-5)
Product condition	1	Level of damage	Extent of rust, corrosion, or other forms of deterioration.	5
	2	Level of fatigue	Extent of material fatigue due to wear from operation.	5
Location of product	3	Geographical location of product	Distance from product to factory.	1
	4	Product placement on vessel	The degree of accessibility for dismantling a product from the vessel is determined by the physical location of the product.	4
Technical specification	5	Material composition	Specific types and proportions of materials or substances used in product.	3
	6	Material value	Value of material.	4
	7	Product documentation	Overview of product history (Maintenance reports, overview of routes).	2
	8	Type of product	Mechanical, hydraulic, electric or software.	5
	9	Technical lifetime	Duration that the product is deemed to be technically reliable and capable of fulfilling its intended purpose.	3
	10	Innovation rate	Technology change rate in the market.	3
External factors	11	Established remanufacture process	Established systematic method for handling reverse flow and remanufacturing practices.	2
	12	Regulations	Regulations that govern maritime operations (classification society, EU..).	4
Product cost	13	Cost of operations new product vs. used	The cost of operating a new product vs. Operating a remanufactured one.	5
	14	Cost difference new product vs. used product	Cost of manufacturing a new product vs. Remanufacture as used one.	5
	15	Product/component value	Premium product or low-cost product.	2
Product structure	16	Design for disassembly	Design for disassembly and separation.	3
	17	Standard components	Interchangeable components.	4
	18	Transferability	Extent to which a product meets the necessary compatibility requirements for successful transfer to a different location or system.	4
	19	Technical complexity	Degree of intricacy and sophistication of its technical aspects, including component count, interdependencies, and specialized knowledge needed for assembly or maintenance.	3
Product performance	20	Quality	Degree to which the product meets requirements and standards.	4
	21	Fuel efficiency	New product vs. Used product.	3
	22	Operational efficiency	Compatibility with a performance range of product.	3

F Factors ranked by Company C

Table 22: Factors ranked by Company C

Categories	No.	Factors	Description	Range (1-5)
Product condition	1	Level of damage	Extent of rust, corrosion, or other forms of deterioration.	4
	2	Level of fatigue	Extent of material fatigue due to wear from operation.	5
Location of product	3	Geographical location of product	Distance from product to factory.	1
	4	Product placement on vessel	The degree of accessibility for dismantling a product from the vessel is determined by the physical location of the product.	2
Technical specification	5	Material composition	Specific types and proportions of materials or substances used in product.	2
	6	Material value	Value of material.	5
	7	Product documentation	Overview of product history (Maintenance reports, overview of routes).	4
	8	Type of product	Mechanical, hydraulic, electric or software.	5
	9	Technical lifetime	Duration that the product is deemed to be technically reliable and capable of fulfilling its intended purpose.	3
	10	Innovation rate	Technology change rate in the market.	3
External factors	11	Established remanufacture process	Established systematic method for handling reverse flow and remanufacturing practices.	3
	12	Regulations	Regulations that govern maritime operations (classification society, EU..).	5
Product cost	13	Cost of operations new product vs. used	The cost of operating a new product vs. Operating a remanufactured one.	5
	14	Cost difference new product vs. used product	Cost of manufacturing a new product vs. Remanufacture as used one.	5
	15	Product/component value	Premium product or low-cost product.	3
Product structure	16	Design for disassembly	Design for disassembly and separation.	2
	17	Standard components	Interchangeable components.	3
	18	Transferability	Extent to which a product meets the necessary compatibility requirements for successful transfer to a different location or system.	4
	19	Technical complexity	Degree of intricacy and sophistication of its technical aspects, including component count, interdependencies, and specialized knowledge needed for assembly or maintenance.	4
Product performance	20	Quality	Degree to which the product meets requirements and standards.	3
	21	Fuel efficiency	New product vs. Used product.	4
	22	Operational efficiency	Compatibility with a performance range of product.	4

G Factors ranked by Company D

Table 23: Factors ranked by Company D

Categories	No.	Factors	Description	Range (1-5)
Product condition	1	Level of damage	Extent of rust, corrosion, or other forms of deterioration.	2
	2	Level of fatigue	Extent of material fatigue due to wear from operation.	4
Location of product	3	Geographical location of product	Distance from product to factory.	4
	4	Product placement on vessel	The degree of accessibility for dismantling a product from the vessel is determined by the physical location of the product.	3
Technical specification	5	Material composition	Specific types and proportions of materials or substances used in product.	4
	6	Material value	Value of material.	3
	7	Product documentation	Overview of product history (Maintenance reports, overview of routes).	4
	8	Type of product	Mechanical, hydraulic, electric or software.	2
	9	Technical lifetime	Duration that the product is deemed to be technically reliable and capable of fulfilling its intended purpose.	3
	10	Innovation rate	Technology change rate in the market.	3
External factors	11	Established remanufacture process	Established systematic method for handling reverse flow and remanufacturing practices.	3
	12	Regulations	Regulations that govern maritime operations (classification society, EU..).	4
Product cost	13	Cost of operations new product vs. used	The cost of operating a new product vs. Operating a remanufactured one.	5
	14	Cost difference new product vs. used product	Cost of manufacturing a new product vs. Remanufacture as used one.	5
	15	Product/component value	Premium product or low-cost product.	5
Product structure	16	Design for disassembly	Design for disassembly and separation.	4
	17	Standard components	Interchangeable components.	4
	18	Transferability	Extent to which a product meets the necessary compatibility requirements for successful transfer to a different location or system.	3
	19	Technical complexity	Degree of intricacy and sophistication of its technical aspects, including component count, interdependencies, and specialized knowledge needed for assembly or maintenance.	4
Product performance	20	Quality	Degree to which the product meets requirements and standards.	5
	21	Fuel efficiency	New product vs. Used product.	4
	22	Operational efficiency	Compatibility with a performance range of product.	4

H Company E

Table 24: Factors ranked by Company E

Categories	No.	Factors	Description	Range (1-5)
Product condition	1	Level of damage	Extent of rust, corrosion, or other forms of deterioration.	5
	2	Level of fatigue	Extent of material fatigue due to wear from operation.	5
Location of product	3	Geographical location of product	Distance from product to factory.	3
	4	Product placement on vessel	The degree of accessibility for dismantling a product from the vessel is determined by the physical location of the product.	3
Technical specification	5	Material composition	Specific types and proportions of materials or substances used in product.	3
	6	Material value	Value of material.	2
	7	Product documentation	Overview of product history (Maintenance reports, overview of routes).	4
	8	Type of product	Mechanical, hydraulic, electric or software.	4
	9	Technical lifetime	Duration that the product is deemed to be technically reliable and capable of fulfilling its intended purpose.	3
	10	Innovation rate	Technology change rate in the market.	3
External factors	4 11	Established remanufacture process	Established systematic method for handling reverse flow and remanufacturing practices.	3
	12	Regulations	Regulations that govern maritime operations (classification society, EU..).	4
Product cost	13	Cost of operations new product vs. used	The cost of operating a new product vs. Operating a remanufactured one.	3
	14	Cost difference new product vs. used product	3 Cost of manufacturing a new product vs. Remanufacture as used one.	3
	15	Product/component value	Premium product or low-cost product.	3
Product structure	16	Design for disassembly	Design for disassembly and separation.	3
	17	Standard components	Interchangeable components.	3
	18	Transferability	Extent to which a product meets the necessary compatibility requirements for successful transfer to a different location or system.	3
	19	Technical complexity	Degree of intricacy and sophistication of its technical aspects, including component count, interdependencies, and specialized knowledge needed for assembly or maintenance.	3
Product performance	20	Quality	Degree to which the product meets requirements and standards.	3
	21	Fuel efficiency	New product vs. Used product.	4
	22	Operational efficiency	Compatibility with a performance range of product.	4

I Company F

Table 25: Factors ranked by Company F

Categories	No.	Factors	Description	Range (1-5)
Product condition	1	Level of damage	Extent of rust, corrosion, or other forms of deterioration.	4
	2	Level of fatigue	Extent of material fatigue due to wear from operation.	5
Location of product	3	Geographical location of product	Distance from product to factory.	3
	4	Product placement on vessel	The degree of accessibility for dismantling a product from the vessel is determined by the physical location of the product.	3
Technical specification	5	Material composition	Specific types and proportions of materials or substances used in product.	3
	6	Material value	Value of material.	3
	7	Product documentation	Overview of product history (Maintenance reports, overview of routes).	4
	8	Type of product	Mechanical, hydraulic, electric or software.	1
	9	Technical lifetime	Duration that the product is deemed to be technically reliable and capable of fulfilling its intended purpose.	4
	10	Innovation rate	Technology change rate in the market.	2
External factors	11	Established remanufacture process	Established systematic method for handling reverse flow and remanufacturing practices.	2
	12	Regulations	Regulations that govern maritime operations (classification society, EU..).	5
Product cost	13	Cost of operations new product vs. used	The cost of operating a new product vs. Operating a remanufactured one.	3
	14	Cost difference new product vs. used product	Cost of manufacturing a new product vs. Remanufacture as used one.	3
	15	Product/component value	Premium product or low-cost product.	3
Product structure	16	Design for disassembly	Design for disassembly and separation.	3
	17	Standard components	Interchangeable components.	4
	18	Transferability	Extent to which a product meets the necessary compatibility requirements for successful transfer to a different location or system.	4
	19	Technical complexity	Degree of intricacy and sophistication of its technical aspects, including component count, interdependencies, and specialized knowledge needed for assembly or maintenance.	3
Product performance	20	Quality	Degree to which the product meets requirements and standards.	4
	21	Fuel efficiency	New product vs. Used product.	2
	22	Operational efficiency	Compatibility with a performance range of product.	3

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