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Improving Demand and Supply Balance in a Closed-Loop Supply Chain: A Case Study in a Dynamic Reuse Spare Part Business

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ABSTRACT:
Many companies have adopted closed-loop supply chain (CLSC) systems in pursuit of greener operations through reuse product offering. Contrary to traditional forward supply chains, CLSCs combine both supply chain directions, forward and reverse. As well, the CLSC incorporates circular manufacturing process into the loop, such as repairing, refurbishing, or remanufacturing. The combination of multiple simultaneous processes leads to added complexity in a circular system. This results in a wide range of challenges faced by a CLSC. The CLSC process challenges present themselves as unbalanced demand for reuse products and supply for returning end-of-use cores. As a result, this study's purpose was to identify the most critical challenges contributing to an unbalanced demand and supply. Also, the study aimed to provide improvement proposals to improve the situation at the case company. To realise this purpose, the study followed the format of a qualitative case study with a maritime company Wärtsilä as the case company. The research data was collected using open interviews with eight key stakeholders involved in the case company's CLSC. Data from the interviews was then transcribed and analysed with a thematic analysis method; categorising found challenges into challenge categories identified from the existing literature. To examine the most critical CLSC challenges, the study performed a criticality analysis using Process Failure Mode & Effect Analysis (PFMEA). PFMEA assigned severity to each found challenge while also evaluating the case company's current methods for prevention and detection. The analysis resulted in 14 different challenge categories expected to contribute to unbalanced demand and supply. Two new challenge categories, challenges with process knowledge and challenges with a missing seeding strategy, were added to the body of knowledge. Regarding criticality, seven challenge categories were found as critical. Critical challenges in reverse supply chain processes related to limited internal and external process knowledge and visibility of returning cores. Critical challenges in circular manufacturing processes related to low core availability, pull-ordering system, outdated inventory management practices, and a missing seeding strategy. Finally, the study proposed improvement proposals for the critical challenges that would result in more balanced demand and supply. These findings stress the individual needs of each CLSC system to perform in an optimal manner. The case company's single source for cores created new challenges that were yet to be identified by the existing literature. Also, the separation of critical challenges aids managers in focusing on the most critical ones in often problem-rich CLSCs.

KEYWORDS: Closed-Loop Supply Chain, Reuse Products, Circular Economy, Spare Part, Single-Source Product, Inventory Management

Contents

1 Introduction 7
1.1 Background 7
1.2 Objectives and research questions 8
1.3 Research gap 9
1.4 Structure of the thesis 9
2 Theoretical background 10
2.1 Circular economy and circularity strategies 10
2.1.1 Circularity strategies in closed-loop supply chains 13
2.1.2 Flows of a closed-loop supply chain 14
2.2 Circular manufacturing 15
2.2.1 Remanufacturing and refurbishing 16
2.2.2 Challenges in circular manufacturing 18
2.3 Managing demand in a closed-loop system 21
2.3.1 Demand forecasting 21
2.3.2 Managing demand uncertainty with inventory 22
2.3.3 Product lifecycle 24
2.4 Managing supply in a closed-loop system 25
2.4.1 Return strategies 25
2.4.2 Forecasting core returns 29
3 Case company and process 31
3.1 Wärtsilä and Wärtsilä Global Logistics Services 31
3.2 Case process 32
4 Methodology 34
4.1 Research design and strategy 34
4.2 Data collection 35
4.3 Data analysis 38
5 Results 39
5.1 Recognised challenges 39

5.1.1 Demand and supply challenges 39
5.1.2 Information and knowledge challenges 42
5.1.3 Material flow challenges 45
5.1.4 Core challenges 50
5.1.5 Operational challenges 51
5.2 Summary of recognised challenges 54
5.3 Analysis of criticality 56
6 Discussion 59
6.1 Theoretical contributions 60
6.2 Improvement proposals for the case company 63
7 Conclusion and future research 67
References 69
Appendices 78
Appendix 1. Predetermined interview questions 78
Appendix 2. PFMEA – Process evaluation criteria tables 79
Appendix 3. PFMEA – Action priority table 81
Appendix 4. PFMEA – Sales 83
Appendix 5. PFMEA – Purchasing 85

Figures

Figure 1. Butterfly diagram by EMF (2019) 12
Figure 2. Value Retention Processes adapted from Nasr et al. (2018) 13
Figure 3. CLSC process flows adapted from Abbey & Guide Jr (2018) 15
Figure 4. Remanufacturing process steps adapted from Steinhilper & Butzer (2019) 17
Figure 5. Remanufacturing process challenges adapted from Kurilova et al. (2018) 19
Figure 6. Product life cycle curve adapted from Kopp (2022) 24
Figure 7. Product lifecycle distributions by Umeda et al. (2005) 30
Figure 8. Availability monthly: reuse fuel pumps and injection valves (Wärtsilä, 2022) 33
Figure 9. Ordering blocking reasons from 2021 – 2022 46
Figure 10. Time spent waiting for cores from 2021 – 2022 46
Figure 11. Orders waiting for cores per product type 2021 – 2022 47
Figure 12. Reuse fuel pump lead times, external supplier 52
Figure 13. Reuse injection valve lead times, internal supplier 53

Tables

Table 1. Research Interviews 36
Table 2. Recognised challenges 54
Table 3. Criteria for severity adapted from AIAG, 2019 and Zhu et al., 2021 79
Table 4. Criteria for occurrence adapted from AIAG, 2019 79
Table 5. Criteria for detection adapted from AIAG, 2019 80
Table 6. Action priority table adapted from AIAG, 2019 81

Abbreviations

AP	Action Priority
CAM	Core Acquisition Management
CLSC	Closed-Loop Supply Chain
EMF	Ellen Macarthur Foundation
EOU	End-Of-Use
EOL	End-Of-Life
ERN	European Remanufacturing Network
EU	European Union
CE	Circular Economy
IPR	Intellectual Property Rights
PFMEA	Process Failure Mode & Effect Analysis
PS	Parts Supply
RL	Reverse Logistics
VRP	Value Retention Process
WGLS	Wärtsilä Global Logistics Services

1 Introduction

Companies operating closed-loop supply chains (CLSC) with reuse products face additional challenges compared to traditional linear supply chains due to circular process setup (He et al., 2020; Kurilova et al., 2019). Kurilova et al. (2018) and Schenkel et al. (2019) have provided an essential overview of the potential CLSC challenges; however, due to the diverse nature of circular systems, not all the challenges have been identified. As well, the criticality of each challenge has not been assessed in the existing literature. This research aims to contribute by examining any new challenges contributing to demand and supply imbalance in a circular system with single-source products. The research also aims to point out the most critical of those challenges. This chapter proceeds to describe the background of this research, followed by objectives and defined research questions. Finally, before closing the chapter, a presentation on the identified research gap and the overall structure of this thesis are provided. The limitations of this study are discussed in the Conclusion and future research - chapter.

1.1 Background

The circular economy has been a trending development direction in recent years when the world aims to decouple economic growth from the depletion of natural resources (Nasr, 2019). The transition towards the circular economy can only be expected to speed up as governmental parties acknowledge it's importance. In Europe, European Commission states that the European Union must transition to a circular economy to realise the union's 2050 climate targets (EC, 2022). The circular economy aims to eliminate pollution and waste by extending products' useful life and circulating products at the highest value (EMF, 2014). When in a traditional linear system, an end-of-use product would be thrown away after use, in the circular economy, this product is taken back for life-extending operations such as repairing, refurbishing, or remanufacturing. Companies have acknowledged the benefits of providing reuse products as an alternative to a new product as reuse offering contributes to all three aspects of sustainable development, environmental, economic, and social (He et al., 2020; Nasr, 2019).

Pursuing circular business models created the need to integrate reverse supply chain operations with traditional forward supply chains (Abbey & Guide Jr, 2017). As a result, this led to the introduction of a closed-loop supply chain (CLSC) system. A CLSC is a system in which the products or materials that have reached the end of their useful life are collected, sorted, processed, refurbished, remanufactured, or recycled back into the same or similar product (Steinhilper & Butzer, 2019; Östlin, 2008). In contrast to linear supply chains, CLSCs are highly complex systems presenting various challenges. These challenges include the management of reverse logistics, quality control, stakeholder collaboration, information management, and compliance with regulations and standards (Battini et al., 2017; Kurilova et al., 2018; Schenkel et al., 2019). Additionally, closed-loop supply chains can suffer from imbalances between the demand for reuse products and the supply of used products or materials due to variability in returns, timing issues, collection and sorting issues, and coordination issues (Kurilova et al., 2018; Steinhilper & Butzer, 2019). The perceived CLSC system challenges vary from each CLSC system to another due to the nature of products and industry-specific requirements (Guide Jr & Van Wassenhove, 2009).

The case company of this thesis offers reuse fuel injection parts for marine engines. After initiating its reuse part programme, the company has been struggling with unbalanced demand and supply. The situation becomes apparent through low and fluctuating stock availability for the reuse parts. The stock availability figures indicate that the company does not satisfy the current level of customer demand. The low availability is expected to arise from the CLSC challenges mentioned above. Additionally, the company's CLSC is further complicated due to single-source products, which prohibits sourcing end-of-use products elsewhere.

1.2 Objectives and research questions

The objective of this research is to identify factors that contribute to unbalanced demand and supply in a CLSC. This is followed by a criticality analysis to highlight the most critical issues. As mentioned above, CLSCs are complex systems with many potential problems

ongoing simultaneously. Therefore, this study aims to filter out the most critical issues for a company's management to focus on. After identifying the most critical issues, the study provides improvement suggestions which, when implemented, should give a better balance in the CLSC. To better guide the research towards its objectives, below research questions were drafted:

1. Why reuse spare parts often suffer from a poor balance between demand and supply?
2. What are the most critical issues regarding demand and supply balance?
3. How should the CLSC be improved to secure a better balance of demand and supply?

1.3 Research gap

This study contributes to the body of knowledge by broadening already identified CLSC process challenges and examining new challenges that can only be observed in a dynamic reuse spare part CLSC with single source products. In addition, this research provides support for managers and future research by narrowing them down to the most critical. This is relevant as companies may not know which challenges pose the most significant performance risk to their operations.

1.4 Structure of the thesis

This thesis has been shared in seven primary chapters. After the introduction, the study proceeds to the theoretical background, laying the ground for the research. From here, the study moves to introduce the case company and case process. This is followed by the methodology chapter, where used research methods are presented. Then the study continues to the results chapter, which is the core of this paper. Finally, the study discusses found results in a discussion chapter before closing the study with conclusions and suggestions for future research.

2 Theoretical background

Here, the applicable theory to this study is reviewed. This section begins with a review of the circular economy as it is an umbrella theme for the remainder of the study. A focus is given to different circularity strategies. This is followed by a look at how circularity strategies connect with closed-loop supply chain (CLSC) management theory, which is the main theoretical framework of this study. From here, the study proceeds to individual CLSC system sub-processes. In the centricity of these chapters are circular manufacturing operations, demand, and supply management.

2.1 Circular economy and circularity strategies

The circular economy has gained growing interest from businesses and organisations recently. The growing concern for depleting natural resources and care for the environment has pushed businesses and decision-makers to look for alternative ways to enable future economic growth. The current linear take-make-waste economy has limitations while causing great harm to the planet (Weetman, 2021). A circular economy may answer these concerns, as it aims to decouple economic growth from using natural resources, which has been the way until now (Ranta & Saari, 2020). European Commission realised the current challenge and adopted the first circular economy action plan in 2015 (European Commission, 2022). The plan was later revised in March 2020. The circular economy action plan is a part of the European Commission's European Green Deal which is to take the European Union (EU) towards sustainable growth and a climate-neutral tomorrow within the continent. With this action plan, European Commission is pushing the EU from a linear economy to a more circular one. Some of the objectives of the action plan are to make sustainability a standard feature of products, empower consumers, reduce produced waste, and take a leading role in the circular economy globally (EMF, n.d.; European Commission, 2022).

Defining the circular economy has proved to be a challenge in academia. This has resulted in many competing definitions. Kircherr et al. (2017) reviewed 114 definitions and

concluded that circular economy means different things to different people. Ellen MacArthur Foundation (EMF) is one of the loudest voices pushing the world towards more circular business models. According to EMF (2021), the circular economy is based on three principles: "*eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature*.". At the core of these principles is the initial design of the product or service. Goods produced for the traditional linear system do not consider what will happen to products at End-Of-Life (EOL). In comparison, products designed with circularity in mind have ways to manage EOL already considered. Managing EOL is at the core of the circular economy (EMF, 2014).

Circularity strategies enable the circular economy. The types and number of circularity strategies can vary depending on the definition of the circular economy. Kircherr et al. (2017) found that the most circular economy definitions included strategies: recycling, reuse, and reduce. Recycling and reuse were mentioned in over 70 per cent of the definitions, while reduce was noted in 54 per cent. Circularity strategies are often described with R-frameworks where 3R is commonly combined from Recycling-Reuse-Reduce and 4R from 3R framework + Recover (Kircherr et al., 2017). Authors have proposed circularity strategies beyond the 3R and 4R frameworks. EMF (2019) presented seven circularity strategies in their butterfly diagram (see Figure 1). The butterfly diagram is EMF's attempt to visualise the circular economy. Here, the left side of the diagram is referred to as the biological cycle, which presents cycles for biodegrading materials. In contrast, the right side of the butterfly diagram is called the technical cycle (EMF, 2019). The technical cycle presents circularity strategies for products in use. EMF circularity strategies are sharing-maintaining-reusing-redistributing-refurbishing-remanufacturing-recycling. Some of the strategies overlap. Other frameworks with more than four strategies are, for example, Potting et al. (2017) definition and framework with nine circularity strategies and Sihvonen and Ritola (2015) with four high-level strategies and six sub-strategies. Their four high-level strategies were Reduce-Reuse-Recycle-Recover. Reuse was divided into six sub-strategies Repurpose-Direct Reuse-Repair-Refurbish-Remanufacture-Resynthesize.

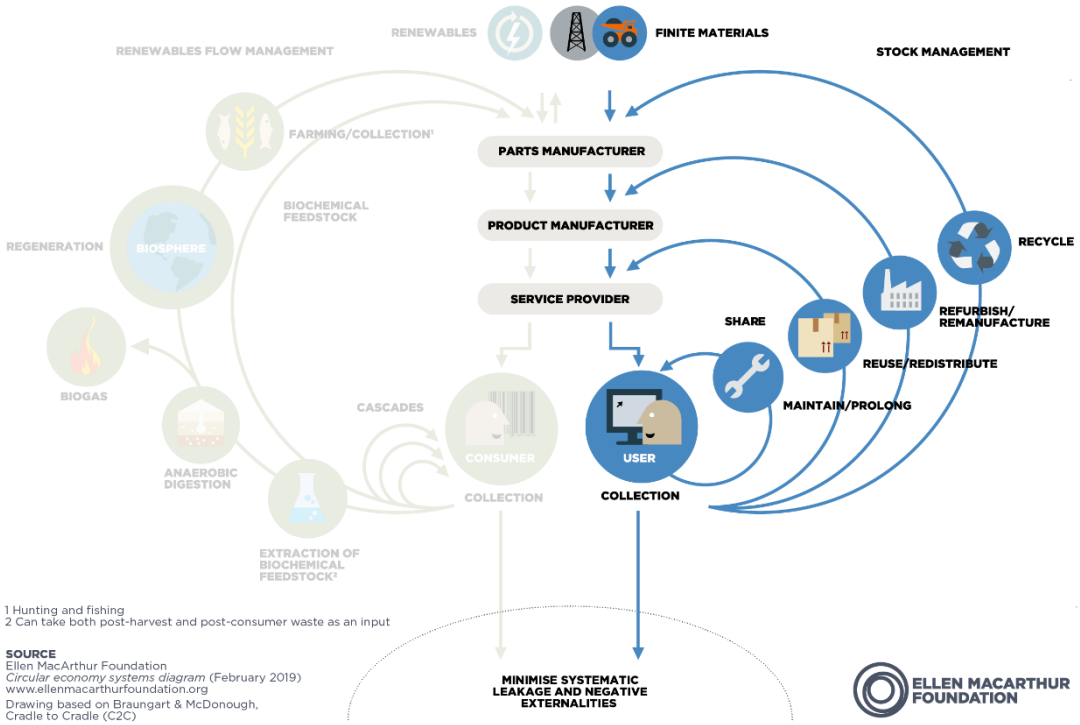

Figure 1. Butterfly diagram by EMF (2019)

Russell and Nasr (2019) and Nasr et al. (2018) have different take on circularity strategies with their Value Retention Processes (VRPs). The VRPs consist of only circularity strategies that allow for retaining products' embedded value at EOL. Therefore, it can be said that the goal of VRPs is to replace the EOL phase with an End-Of-Use (EOU) phase. Recycling, which is seen as a cornerstone of the circular economy (EMF, 2019; Kircherr et al., 2017), is not listed as a VRP because products lose their embedded value when recycled. The embedded value comprises energy, labour, and other resources needed to produce the product (EMF, 2019). According to Russell and Nasr (2019), there are two categories of VRPs with five separate processes (see Figure 2). Full-service VRPs are remanufacturing and comprehensive refurbishment. Full-service VRPs ensure full or almost full-service life to a product after going through a VRP. The second category is partial service life VRPs. These are direct reuse, repair, and refurbishment. Among partial service life VRPs, the VRP operations only partially renew the product's service life. Partial-service life VRPs generally have shorter lifecycles in comparison to full-service life VRPs. This, however, is highly dependent on the type of product (Russell & Nasr, 2019). Nasr et al. (2018) emphasise that material recycling cannot be avoided entirely, as no product has an

indefinite lifetime. VRPs ensure that the product's function and embedded value are maintained as long as possible. When this is not viable anymore due to degradation, then products become a subject for recycling. Products are recycled for raw materials and components that can be used in actual VRPs, before what is left over to an incineration plant for energy recovery (Nasr et al., 2018).

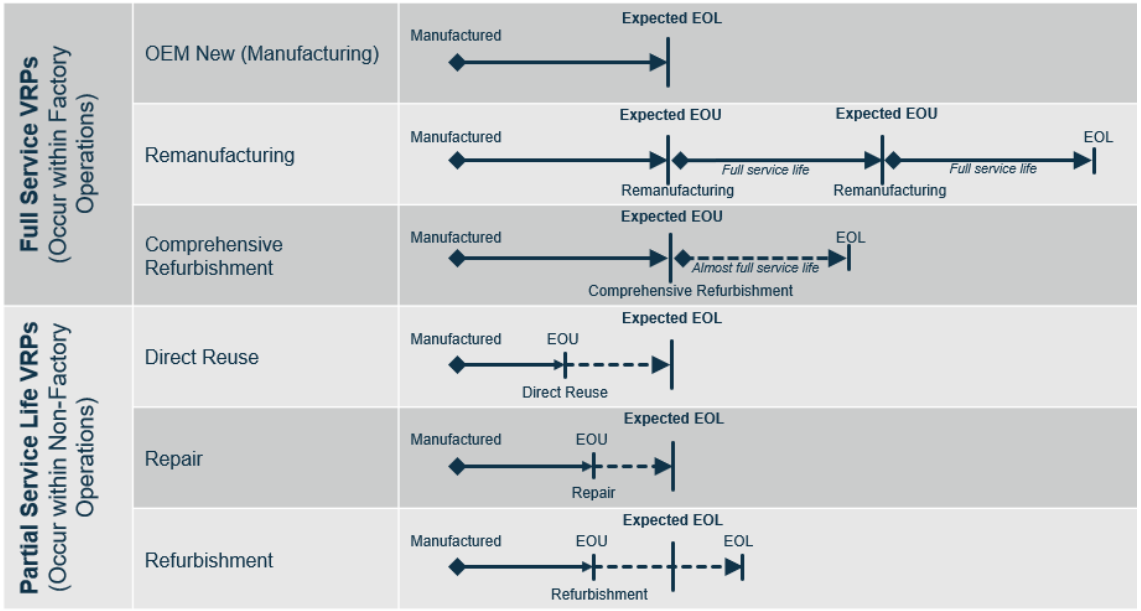

Figure 2. Value Retention Processes adapted from Nasr et al. (2018)

2.1.1 Circularity strategies in closed-loop supply chains

Circularity strategies and Closed-Loop Supply Chain (CLSC) management are topics that go hand in hand. Whereas circularity strategies aim to create product flow loops, CLSC management provides the strategies to manage these loops (Russell & Nasr, 2019; Souza, 2017, p. 5). Guide Jr. and Van Wassenhove (2009) define CLSC management as "*the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time.*". CLSC management can be shared into three sections: the engine, demand side processes, and supply side processes (Abbey & Guide Jr, 2017; Priyono et al., 2012). The engine is a circularity strategy that acts as an "engine", creating flows and requirements for supportive processes. Abbey and Guide Jr (2017) include

remanufacturing as their circular system engine. However, the engine could be refurbishing or any other circularity strategy that uses EOU products as process inputs. Returning EOU products are called “cores” in the CLSC context (Russell & Nasr, 2019). Demand-side processes aid in managing the demand uncertainty of a CLSC system. These activities aim to drive reuse product sales and ensure products reach the market (Abbey & Guide Jr, 2017). Reuse product demand forecasting is at the core of demand management (Matsumoto & Komatsu, 2015; Priyono et al., 2012). Supply processes manage the sourcing and returning of cores from the field for circular manufacturing operations with acquisition management. A well-functioning acquisition management process is the cornerstone of a CLSC, helping to alleviate supply uncertainty in the system. Without a sufficient flow of cores, the company pursuing circular manufacturing will run into issues eventually (Abbey & Guide Jr, 2017). Only when all three activity categories, the engine, demand, and supply processes, are in line can CLSC perform as expected to create a profitable business (Abbey & Guide Jr, 2017; Guide Jr & Van Wassenhove, 2009).

2.1.2 Flows of a closed-loop supply chain

Figure 3 presents a visualisation of theoretical flows in the CLSC. The circular flow begins as goods enter the market through forward supply chain activities. After the customer use period, goods start their reverse journey. Some products go directly to the EOL waste stream due to wear. At the same time, the remainder of EOU goods become cores entering the reverse supply chain as raw materials and sub-components. Manufacturers manage core returns with the aforementioned acquisition management process. The acquisition management process is reviewed later in more detail. From the acquisition management, the cores are shared into different circular manufacturing activities (Abbey & Guide Jr, 2018). Some organisations have incorporated core quality grading in their acquisition process, guiding incoming cores to subsequent processes based on core quality (Wei et al., 2015). In Figure 3, component and product reprocessing phases present cores’ life extension processes such as refurbishing and remanufacturing. Here, the circular manufacturing process renews cores back to the market or the forward

supply chain as sub-components. Any unfit parts continue to recycling (material reprocessing in Figure 3). Salvageable material is fed back into the forward supply chain, and non-salvageable material moves to the EOL waste stream (Abbey & Guide Jr, 2017).

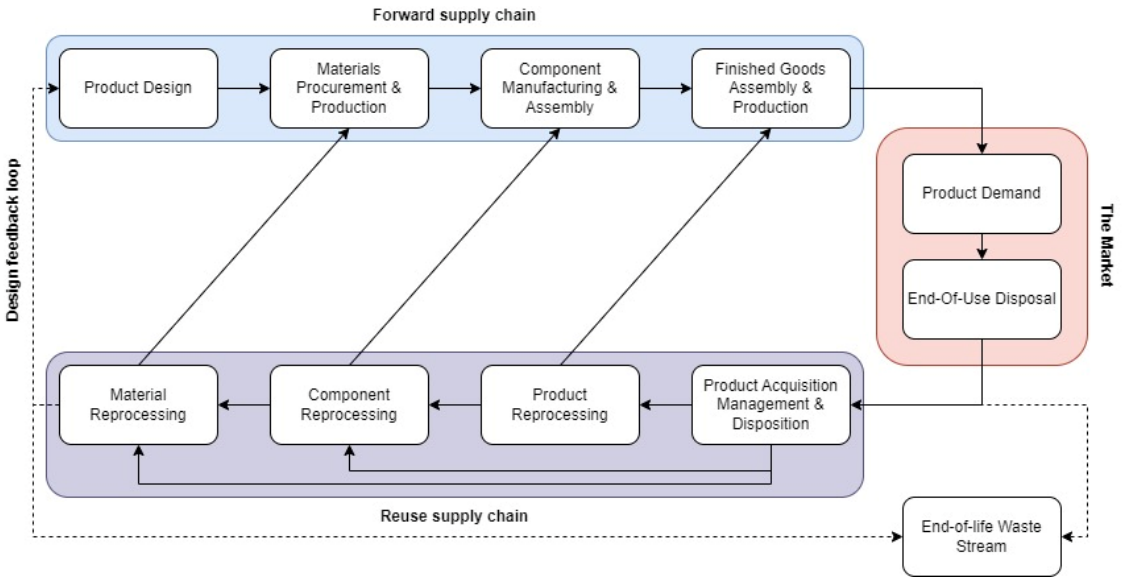

Figure 3. CLSC process flows adapted from Abbey & Guide Jr (2018)

The following chapters dive deeper into three activity categories within CLSC, starting with circularity strategy as the process engine. From here, the study continues to demand management, focusing on demand forecasting. The theoretical part is concluded with supply activities with acquisition management processes.

2.2 Circular manufacturing

Remanufacturing is the most widely discussed circularity strategy in CLSC literature. MahmoumGondabi et al. (2021) reviewed the literature on the circular economy within the CLSC context; 117 articles of 254 discussed remanufacturing, the most extensive portion before other circularity strategies. The high share of remanufacturing articles could be partly explained by challenges related to defining different circularity strategies. Nasr et al. (2018) highlight that the definitions of circularity strategies vary between industries and even company-level differences have been observed. A company may address its goods as remanufactured, while the correct term may have been refurbished

or repaired (Chen & Chen, 2019). As an example of the terminology challenge, ERN, in their publication by Parker et al. (2015), observed that the machinery sector in Europe used the terms “rebuild” or “retrofitted” for remanufactured goods. Other commonly met terms were “reconditioned” and “refurbished”. The terminology was found to vary also between companies and countries (Parker et al., 2015). As a result, the remainder of this study avoids separating different circular manufacturing strategies and mainly supports on literature from remanufacturing. In the text, circularity strategies are referred to as “*circular manufacturing”* and finished circular manufacturing products as *“reuse products”.* The next chapter provides a view of often used circularity strategies in the CLSC context, remanufacturing and refurbishing.

2.2.1 Remanufacturing and refurbishing

Remanufacturing and refurbishing have grown in importance due to their contribution to all three aspects of the triple bottom line, economic, environmental, and social. These operations create economic opportunities, lower environmental impact through more resource-efficient processes, and contribute socially through created jobs (Russell & Nasr, 2019). From an economic and social perspective, remanufacturing, as an example, has gained ground since it is currently a multi-billion-dollar industry globally, led by the United States as the most significant contributor. In Europe, remanufacturing industry generated around 30 billion Euro turnover while employing around 190.000 people in 2015. European Remanufacturing Network (ERN) estimates remanufacturing to reach 70 – 100 billion Euro turnover by 2030 (Parker et al., 2015). Remanufacturing and refurbishing are also vital environmentally. Nasr (2019) highlights the importance of these activities, as these keep products out of recycling and landfills by retaining the product’s function and embedded value. At the same time, these processes require a reduced amount of energy and resources compared to manufacturing. A remanufactured Caterpillar cylinder head requires 85 per cent less energy than a manufactured one (Caterpillar, 2021).

Figure 4. Remanufacturing process steps adapted from Steinhilper & Butzer (2019)

Remanufacturing is a thorough process where the remanufactured product is renewed with a new full-service life (see Figure 2) (Russell & Nasr, 2019). It is referred to as:

> A comprehensive and rigorous industrial process by which a previously sold, leased, used, worn, remanufactured, or non-functional product or part is returned to a like-new, same-as-when-new, or better-than-when-new condition from both quality and performance perspective, through a controlled, reproducible and sustainable process. (ANSI, 2021)

Nasr (2019) adds to the above definition that a remanufacturing process is typically carried out in an industrial facility or a factory. According to Steinhilper and Butzer (2019), the traditional remanufacturing operation has five steps: disassembly, cleaning, inspection, reconditioning, and reassembly (see Figure 4). During the process, worn-out parts are either restored to their original state or replaced by an alternative working component. Products that contain many electronics usually require a six-step process as the process begins with an entrance diagnosis. Sundin (2004) takes a similar view by mentioning that a remanufacturing operation comprises steps: cleaning, inspection, disassembly, storage, reprocessing, reassembly, and testing in a varying sequence. The

arrangement and type of remanufacturing activities depend on the industry and the remanufactured product (Steinhilper & Butzer, 2019; Sundin, 2019). Other impacting factors include raw material sources, demand level, and industry-specific regulations (Sundin, 2019).

Refurbishing is defined as: "*Return a product to good working order. This can include repairing or replacing components, updating specifications, and improving cosmetic appearance.*" (EMF, 2021). Russell and Nasr (2019) share a similar view mentioning that a refurbishing operation can result in a new partial-service life but not a new full-service life (see Figure 2). The International Resource Panel, in their publication by Nasr et al. (2018), mention that some industries have a refurbishment process that is closer to remanufacturing than refurbishing. This process is called comprehensive refurbishing. The definition follows the lines of traditional refurbishing but comprehensive refurbishing "*takes place within industrial or factory setting, with a high standard and level of refurbishment*" (Nasr et al., 2018). The process of refurbishing often follows similar steps as remanufacturing while being less structured and resource-intensive (Nasr et al., 2018). Reconditioning is a competing term for refurbishing; on many occasions, these are considered equal. For example, International Standard Organization considers reconditioning and refurbishing interchangeable terms (ISO, 2017). As well, one can notice similarities in EMF's (2021) above refurbishing definition and BSI's (2009) reconditioning definition, which is an action that "*return a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components.".* Both definitions aim to bring a product into good or satisfactory working condition.

2.2.2 Challenges in circular manufacturing

A circular manufacturing system faces many operational challenges due to a complex process setup. Kurilova et al. (2018) reviewed 119 articles on remanufacturing system challenges and categorised them into industry, system, and process levels (see Figure 5). The industry-level challenges include legislation and environmental regulation, customer

preferences and technological change. In comparison, the system challenges involve the product's lifecycle phases and interaction between process stakeholders. Finally, the process level challenges are observed in the workshop floor where cores are remanufactured to new condition (Kurilova et al., 2018). When studying remanufacturing challenges with four case companies, Kurilova et al. (2018) observed challenges from seven challenge categories out of all presented in Figure 5 that had an immediate effect on system performance. Three challenge categories from the system level were observed: *demand and supply*, *material flow*, and *information and knowledge*. Challenges on the process level were studied in greater detail as the study covered categories: *core*, *operations*, *product*, and *costs* (Kurilova et al., 2018).

Figure 5. Remanufacturing process challenges adapted from Kurilova et al. (2018)

On the system level, *demand and supply* challenges create the most trouble in circular systems (Goltsos et al., 2018; Kurilova et al., 2018). The main challenge is balancing demand with the stochastic nature of core returns. An unbalanced situation can lead to overstocking or stockouts where reuse parts are unavailable when needed (Guide Jr, 2000). Demand and supply challenges result when a company lacks tools to match the

number of core returns with reuse part sales. Balancing demand and supply require often forecasting both supply of returning cores and the demand for finished reuse products. Challenges arising from complex reverse supply chain network and core collection point infrastructure also create demand and supply challenges, as complex return network contributes by adding unpredictability to core returns (Kurilova et al., 2018). *Material flow* challenges are closely related to the above-mentioned demand and supply challenges. The varying flow of cores can create challenges for the company's inventory control and management practices. Similarly, unmanaged replacement sub-components may extend process lead times, eventually leading to excess sub-component inventories or stock-outs when the demand is high (Kurilova et al., 2018). Challenges in poor process *information and knowledge* can lead to added processing time. In a circular system, information regarding a returning core is valuable. Valuable information for the circular manufacturing operator could be returning product type, model, manufacturing year and condition (Kurilova et al., 2018). Similarly, information about reuse part demand is vital in circular manufacturing (Matsumoto & Komatsu, 2015). Without prior information, the company cannot start operative preparations beforehand. For example, replacement part sourcing and production planning may have to wait until the core has returned.

On the process level, *core* challenges contribute the most to extended and varied lead times disturbing reuse product supply. Core challenges result from difficulties acquiring and managing core components (Kurilova et al., 2018). Additionally, the core category covers challenges related to the problem of evaluating cores' remaining useful life and deciding on the optimal time for the product's life-extending operation. These challenges result from the quality, quantity, and timing issues in returning cores (Wei et al., 2015). A company is required to do some level of quality categorisation to separate non-manufacturable parts from parts that are too degraded and therefore are ready for recycling. *Operations* challenges have a significant impact on reuse product lead time. Without the possibility of planning beforehand, the time needed for the work is difficult to estimate, which can lead to long processing and waiting times. Additionally, since cores return in varying conditions, the labour and resources required per core can vary

significantly (Guide, 2000; Kurilova et al., 2018; Rönkkö et al., 2021). Remanufacturing *product* challenges result from customers' reliability and safety concerns about remanufactured goods. Therefore, remanufactured products need similar quality controls as newly manufactured goods (Kurilova et al., 2018). Finally, managing and controlling costs can be challenging with reuse products, as the resources needed per unit can differ due to varying core conditions. Parts not fit for circular manufacturing should be filtered out from the process to avoid processing parts that are too degraded (Kurilova et al., 2018).

2.3 Managing demand in a closed-loop system

As mentioned in the Challenges in circular manufacturing-chapter, a well-performing CLSC requires the circular manufacturer to balance the demand for reuse parts with the supply of cores. An unbalanced situation can lead to unfavourable situations such as stock-outs when demand surpasses supply or excess stock value when supply is high and demand is low (Östlin, 2008). Both are unfavourable situations in the eyes of a circular manufacturer. This chapter presents how companies can manage demand with forecasting, inventories and how product lifecycle status affects CLSC.

2.3.1 Demand forecasting

Demand forecasts are an efficient way to balance the situation from the demand point of view. A demand forecast provides an estimated view of future events that aid the company in evaluating requirements for operations and material supply (Krajewski & Malhotra, 2022, p.314). An effective demand forecast requires cross-functional collaboration from sales and marketing to operations and supply chain management. The latter two plan operational factors, such as production output, inventory levels, and service and material procurement, based on the provided forecast (Krajewski & Malhotra, 2022, p.315). Multiple forecasting techniques are available, and each has strengths and weaknesses depending on what is being forecasted. Forecasting techniques are shared into two method types, judgment-based and quantitative.

Judgment methods are qualitative forecasting technique that predicts future demand based on non-historical demand data (Krajewski & Malhotra, 2022, p.315). The demand forecast is often built by looking at past events. However, there are cases where historical data is not available. A good example is a new product introduction where sales personnel do not have past demand to support. In this case, the sales personnel use their best judgment and expertise to create an estimation of the demand. Similarly, a quantitative forecast can be adjusted with judgement methods if the sales organisation knows that some market conditions will impact the demand (Chopra, 2019, p.188). Judgment methods build forecasts on sales personnel estimates, executive opinion, and market research (Krajewski & Malhotra, 2022, p.323).

Quantitative forecasting methods include multiple quantitative forecasting tools such as causal methods, time-series analysis, and trend projection using regression (Krajewski & Malhotra, 2022, p.315). All of these tools rely heavily on historical data to predict future demand. Causal methods create a forecast by analysing how independent factors impact demand. When using causal methods, the company must first identify the factors influencing future demand and how strongly each factor contributes to total forecasted demand (Chopra, 2019, p.188). Commonly analysed factors are promotional campaigns and economic conditions. Time-series analysis builds future demand forecasts on what happened in the past during that same period. Time-series analysis is widely used due to its easy-to-use nature and the fact that many companies have access to their past demand data. Trend projection using regression is a method that uses both causal methods and time-series analysis to generate a demand forecast. This method allows managers to combine the predicted impact of independent variables with past demand data to estimate next-period demand (Krajewski & Malhotra, 2022, p.318).

2.3.2 Managing demand uncertainty with inventory

By holding inventory, a company can alleviate demand and supply uncertainty. The uncertainty results from the fact that the company does not know how many pieces and in what time interval customers are purchasing (Krajewski & Malhotra, 2022, p. 363). A

demand forecast helps somewhat, but this is only the best estimate. There are multiple types of inventories, but here the study focuses on a safety inventory and cycle inventory. The safety inventory allows companies to prevent stockouts when actual demand is higher than what was forecasted. It is a buffer of excess products that able the company to handle that additional demand. The safety inventory aid companies in preparing for other supply chain challenges, such as a variable amount of supply and lead times from suppliers. The safety buffer also allows the company's operations to continue through turbulent demand and supply conditions (Chopra, 2019, p.325).

Most companies with supply chain operations build some cycle inventory. A cycle inventory results when a company produces or purchases products in lots of multiple products rather than the exact amount demanded by the customer (Chopra, 2019, p.278). Why companies handle products in lots rather than by a single unit has to do with cost optimisation. Managing the supply of products in lots allows companies to lower material and processing costs through economies of scale. The lot size is defined based on ordering or production intervals. If a lot is ordered every ten weeks, one lot must cover the 10-week demand. The cycle inventory level is at its highest when the new lot arrives at the start of the time interval. While the cycle inventory is at its lowest at the end of the time interval just before the arrival of the new lot (Krajewski & Malhotra, 2022, p. 363).

Effective inventory management is a balance between having enough materials available to satisfy demand and not having too much, which would result in high inventory holding costs (Krajewski & Malhotra, 2022, p. 360). A company's important inventory performance indicator is product availability, also known as customer service level. Product availability measures how effectively a company satisfies customer demand from available inventory (Chopra, 2019, p.372). A high product availability figure means that customer demand is well satisfied. To reach high availability figures, the company is required to hold more extensive inventories, which results in higher inventory-holding costs. A well-adjusted availability target satisfies customer demand while optimising cost. Also, a correct availability level maximises supply chain profits (Chopra, 2019, p.372).

2.3.3 Product lifecycle

The product lifecycle stage is a factor that can have a significant impact when balancing demand and supply in a reuse CLSC. The lifecycle stage influences quantities sold, eventually affecting how many cores return for circular manufacturing (Atasu et al., 2008). During the product introduction and growth phase, the demand for reuse products can be high while the supply for cores is close to none (Östlin et al., 2009). To balance the situation, the manufacturer must support on other sources of cores. A manufacturer that can acquire cores from additional sources can get ahead of the competition. One method to increase supply is to use a seed stock of new components (Östlin et al., 2009). Cores will eventually start to return from the field when first sold products are nearing the EOU state. When the first cores return, the circular manufacturer has a sense of urgency to manufacture those parts as soon as possible to fulfil the high demand for reuse products (Östlin et al., 2009).

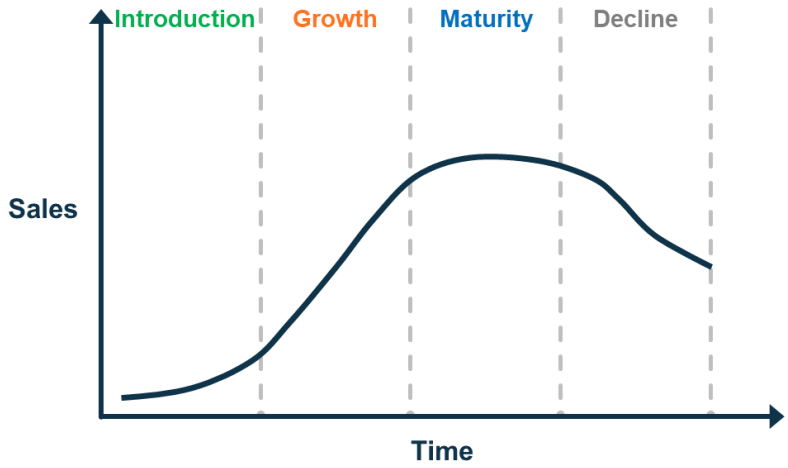

Figure 6. Product life cycle curve adapted from Kopp (2022)

When products are past the growth stage and start to enter maturity, returning core quantities and demand for reuse products can be expected to be more in balance (Guide Jr et al., 2000; Östlin, 2008). In Figure 7, product sales start to plateau first time after a rise period. In the decline phase, the demand for reuse products starts to get lower while the supply of cores is higher. This shifts the demand and supply balance. The main challenge of the decline phase is high core and reuse product inventories. If the product

has moved to a newer version, the circular manufacturer can consider upgrading older declining version products to the latest version, which would decrease inventories and avoid obsolescence. Also, the updated old product can aid in fulfilling the high demand for newly released products (Östlin et al., 2009).

2.4 Managing supply in a closed-loop system

Managing the supply of cores is equally crucial when balancing the scale between demand and supply. Authors have proposed acquisition management practices for managing returns to make the supply more manageable. Wei et al. (2015) propose a Core Acquisition Management framework built on the original Product Acquisition Management framework from Guide Jr and Jayaraman (2000). Core Acquisition Management (CAM) aims to secure a better balance between demand and supply by providing tools to manage core returns (Abbey & Guide Jr, 2017; Guide Jr & Jayaraman, 2000; Wei et al., 2015). CAM is defined as "*the active management of the core acquisition process in remanufacturing to achieve a better balance between return and demand, by dealing with the uncertainties in terms of return volume, timing, and quality"* (Wei et al., 2015). CAM is combined of three core activities: return strategies, core acquisition control, and forecasting core return (Wei et al., 2015). Core acquisition control is presented as a sub-theme for return strategies as Wei et al. (2015) found out that literature equates core acquisition control to acquisition effort, i.e., how much a remanufacturer should pay for cores to motivate return behaviour. Since this theme is visited in return strategies, the acquisition control is included there as a sub-theme. The report continues to core return strategies before returns forecasting.

2.4.1 Return strategies

A company can enhance their control on returning cores by applying a correct return strategy. Östlin et al. (2008) studied return strategies under circular supply chain relationships. They identified seven relationship types within researched

remanufacturing case companies: *ownership-based, service-contract, direct order, deposit-based, buy-back, and voluntary-based*.

In *ownership-based relationships*, a product is provided to a customer for use while still owned by the vendor (Östlin et al., 2008). This strategy is typical in rental, leasing or product-as-a-service business models. The ownership-based relationship is a strong bond between the two parties requiring two-sided cooperation. Often in ownership-based relationships, the seller is responsible for ensuring that the product performs as expected; therefore, the seller is responsible for maintaining or replacing the product during the contract period. In terms of core recovery, this kind of relationship allows the service provider to monitor the condition of their installed base in steady intervals. This enhances supply chain visibility allowing better operations planning.

The service contract relationship shares many similarities with the ownership-based contract. The main difference is that in the service contract relationship, the ownership of the product has moved to the customer (Östlin et al., 2008). This naturally reduces the seller's control of the product. Service contracts move the ownership to the customer but state that lifetime extension activities such as remanufacturing must be done according to specific intervals at the seller's workshop. From a core recovery point of view, service contract relationships can be problematic, as returning a product for maintenance can mean a stop of operations for the customer. Service contract relationships require planning from both sides to support all parties (Östlin et al., 2008).

In the *direct-order relationship,* the customer sends a product to a workshop for remanufacturing. This type of exchange is also called a make-to-order service. From a service provider point of view, this relationship model has many benefits since most of the risk has been pushed on the customer's side. The service provider does not necessarily need to hold an inventory of cores as it is for other mentioned relationships. The customer supplies the cores to the process. From the customer's point of view, direct order relationships can be problematic for the same reason as service contract

relationships. When the product is sent to a service provider for operation, this can mean a stop of operations until the product has returned. Additionally, the remanufacturing cost is unknown before the remanufacturer has inspected the part and determined the resources needed for the operation (Östlin et al., 2008).

In a *deposit-based relationship,* the customer acts as the core source. When purchasing a remanufactured product, the customer must return the old EOU core in exchange (Östlin et al., 2008). This relationship type does not consider the quality of the EOU deposit core when returned. In theory, this type of relationship creates a 1-to-1 match between demand and supply. In reality, the return rate is still not 100 % due to complexities in the process. For example, the part can get lost in delivery, or a remanufacturer's sales personnel fail to demand a product return from the customer. The benefits of this type of relationship are apparent as the customer is provided with a working reuse product when the EOU core is returned. Therefore, any disturbances to customer's operations can be minimised. The deposit-based relationship is an excellent way to secure higher return rates but is still subject to timing challenges. Since the first core source is the customer, the vendor may need to support on a seed stock of new components to enhance reuse part availability. This is especially important at the beginning of market introduction as cores will only start returning when parts wear closer to EOU and become subject to replacement (Östlin et al., 2008).

The credit-based relationship is similar to the deposit-based relationship, except instead of a deposit, the customer receives credits for their EOU part returns. According to Östlin et al. (2008), other differences are that customers can return more than one product since the exchange is not bound directly to a product delivery like it is in the deposit-based system. Also, the returned cores are often ranked based on the return condition. Cores in better condition receive a higher amount of credit than lower-quality cores. The remanufacturer can also pay higher credits for high-demand items to incentivise more frequent returns. The attained credits can be later used in other purchases. This type of system gives the remanufacturer some tools to manage demand and supply. Though,

more return flexibility to the customer results in more uncertainties at the remanufacturer's end. Other challenges can be how to control customers' use of credits. If the customer returns old products of low value and exchanges these credits for a high-value product, there is a good chance that the vendor ends up making a loss. The complex crediting system also tends to require more administrative resources from the service provider (Östlin et al., 2008).

In *buy-back relationships*, the remanufacturer buys the cores for its remanufacturing operations. The potential sources can be dealers who have specialised in sourcing cores, scrap yards, or customers. The buy-back relationship is the most commonly used in remanufacturing companies (Sundin et al., 2016; Östlin et al., 2008). This relationship type is either the primary way to source cores or buying cores is used to support other core sourcing relationships. A well-functioning buy-back relationship often requires a deeper relationship with the core supplier. The competition can be fierce, and each remanufacturer wants to source the best cores at the best price. Core acquisition control is mainly applied in the buy-back relationship since the remanufacturer may have an urgent need for cores. Therefore, they are willing to pay a higher price (Wei et al., 2015). By changing the acquiring price, the remanufacturer has some tools to control the timing, quality and quantity of returning cores (Guide Jr & Jayaraman, 2000; Wei et al., 2015). Besides the buy-back relationship, control can also be applied in credit and debit relationships though the effectiveness may be limited.

Voluntary-based relationships rely on customers' willingness to return the product after use voluntarily. Governments can force this type of relationship with directives that require companies to take back cores. This type of relationship is often found in the recycling business. A good example is empty toner cartridges which are hazardous waste with additional recycling requirements. A remanufacturer can provide means to recycle the cartridges while collecting valuable cores for remanufacturing with little cost. The costs for the remanufacturer associated with this type of relationship are only transportation and material handling costs (Östlin et al., 2008).

Caterpillar and their Reman programme are commonly used as an example when discussing remanufacturing of machinery. Caterpillar has adopted a credit-based return strategy to incentivise core returns. When customers return a core, they receive a credit that can be used for another Caterpillar Reman product (Caterpillar, 2022). The returning process begins when a customer returns EOU core to a Caterpillar dealership. Here the core goes through visual inspection, and the customer is given credit based on the core condition. Cores must meet specific criteria to be credited, and cores in better condition often receive higher credit than those of lesser condition. Jeff Gutzwiller, Caterpillar Reman product manager, points out that a core in better shape can be remanufactured for less cost and resources (Caterpillar, 2022). From the dealership, the cores are then delivered to Caterpillar's global core sourcing facility for sorting before sending them to a remanufacturing factory.

2.4.2 Forecasting core returns

Forecasting core returns is often seen as an essential element of the circular manufacturing system (Guide Jr & Jayaraman, 2000; Matsumoto & Komatsu, 2015; Östlin et al., 2009;). Forecasting core returns refers to estimating when a core returns for circular manufacturing operations (Goltsos et al., 2018). As mentioned in earlier chapters, the information on returning core can be precious for the company (Clottey et al., 2012; Kurilova et al., 2018; Priyono et al., 2012; Östlin et al., 2009). The current forecasting systems are built on the understanding that product returns tend to follow a normal distribution (Goltsos et al., 2018). Therefore, a forecast could be made on past product sales data (Priyono et al., 2012; Östlin et al., 2009). Figure 6 presents a distribution of product sales and product disposals. Here, average product life is used to predict the timing of core returns. With a sales date known, a company would have a good guess on when the product is about to be due for replacement. In this kind of system, factors such as the forecasted product type, the rate of technology innovation, mean product lifetime, and failure rates impact the forecast system design (Östlin et al., 2009). For example, Clottey et al. (2012) developed a forecasting model to derive the distribution of used product returns. This information was coupled with a case company's production

planning and control operations. The case company reduced onhand inventory through this setup, resulting in cost savings. Examples of forecasting studies in remanufacturing using past return data and new product sales data are Geda and Kwong (2021) and Liang et al. (2014).

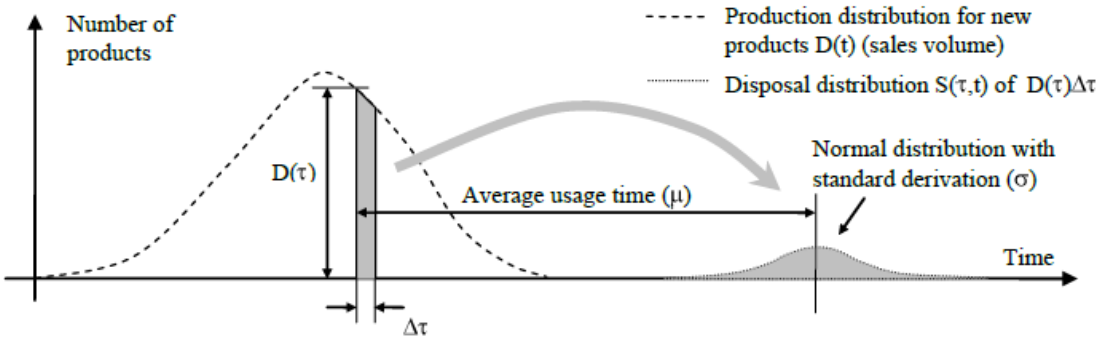

Figure 7. Product lifecycle distributions by Umeda et al. (2005)

Many authors agree that forecasting core returns are a rather complex endeavour with many moving parts that limit the forecast accuracy (Goltsos et al., 2018; Wei et al., 2015). Due to this, only a limited number of studies have been done on this topic (Wei et al., 2015). A return forecasting system may help to provide a rough image of returning cores, but it will lack accuracy due to the dynamic nature of supply chains (Souza, 2017, p. 100). Returning cores may face obstacles, for example, in logistic or customs processes that, as a result, hinder the core's return journey. As a result, the number of returning cores will always be lower than the disposal distribution. Another challenge of the returns forecasting system is incorporating returning core quality into the forecast. Cores are returned in varying quality, of which only a certain amount are still fit for circular manufacturing (Goltsos et al., 2018). Among academia, forecasting for reuse product demand has been a more studied field in the CLSC context (Goltsos et al., 2018).

3 Case company and process

This chapter describes the case company and the business unit affiliated with the case process. Similarly, a brief description of the case process is given.

3.1 Wärtsilä and Wärtsilä Global Logistics Services

Wärtsilä is a multinational company founded in 1834 (Wärtsilä, 2022). The company offers an extensive portfolio of products and services to marine and energy markets, with a total annual revenue of around 5 billion Euros. It has a global presence with over 200 locations in 68 countries, employing approximately 17,000 professionals. Wärtsilä's core offerings for marine markets are ship engines, propulsion products, and marine systems. The offering for energy markets consists of engine power plants, energy storage solutions, and associated optimisation systems. Both business units mentioned above are supported by Wärtsilä services which make an essential part of the company. Due to their product offering, the company is positioned in the middle of tomorrow's clean transportation and energy generation. Wärtsilä has acknowledged this as decarbonisation is a leading strategic priority for the future. Currently, the company is developing engines that run on low and eventually zero-carbon fuels (Wärtsilä, 2022).

Wärtsilä Global Logistics Services (WGLS) is a business unit within the Wärtsilä corporation. The responsibility of WGLS is to manage the complete logistical chain for Wärtsilä Spare Parts, from order intake to customer delivery (Wärtsilä, 2021). WGLS organisation comprises six smaller entities, Parts Coordination Management, Parts Supply, Parts Delivery, Operations Support, Supply Management, and Global Customs Management. The central case organisation of this study is Parts Supply (PS) which manages activities such as sourcing, purchasing, quality, inventory planning and customs data expertise. In other words, Parts Supply manages the whole process of incoming goods from suppliers to stocking in the WGLS warehouse. PS manages approximately over 1 million different materials, of which around 40.000 thousand are managed actively. Annually the organisation processes more than 100.000 order lines (Wärtsilä, 2021).

3.2 Case process

The case organisation's reuse parts programme holds the name Exchange parts process. It has seen multiple iterations; the latest revision was released in March 2022 (Wärtsilä, 2022). The case company refers to reuse components as "exchange parts" and EOU cores as "exhausted parts". An exchange part can be a reuse component or a completely new component. The share of reuse parts presents a marginal portion of the case company's spare part business. It amounts to 1 per cent of total sales but is expected to grow rapidly in the upcoming years (Wärtsilä, 2022). The case company approaches the reuse parts market by defining three market positions: defensive, strategic, and business-driven. Parts with defensive market position alleviate price-lowering pressure from new components by offering a lower-priced reuse alternative. This allows the company to reach price-critical customers. Strategic components are the case company's core business as the components contain Wärtsilä technology. The reuse parts programme enables the collection of used parts from the field, which helps the company to protect its intellectual property. Parts with business-driven market position aim to produce profitable business for the company without further strategic goals. Across all reuse parts, the incentive for a customer to buy a reuse part is a lower price compared to the price of a new component. Reuse parts are promised the same warranty and performance guarantees as new components (Wärtsilä, 2022).

The case organisation offers a variety of engine parts that have a reuse option available. This study focuses on 4-stroke reuse spare parts. The 4-stroke reuse engine parts category consists of parts such as fuel pumps, injection valves, and cylinder heads. This study takes fuel pumps and injection valves under closer scrutiny. The scope consists of two fuel pump types and three injection valves. In a nutshell, the process cycle begins by selling a customer a reuse part. When the reuse part is delivered to the customer, the replaced EOU core is returned to Wärtsilä logistic centre by the customer. After recovering the core, it is sent to Wärtsilä's workshop or an external supplier for circular manufacturing. After the operation, the part is returned to the logistic centre as a reuse part. At the warehouse, the part is stocked until yet sold again (Wärtsilä, 2022).

The reuse parts programme involves stakeholders across the whole organisation. The spare parts sales team is the leading party guiding the process as they initiate the cycle by offering the customer a reuse part. Similarly, the sales team is responsible for ensuring that cores are returned. Other essential parties are workshop personnel, purchasing team and inventory planning, who guide the circular manufacturing operation between the logistic centre and the workshop. The purchasing team and inventory planning are responsible for securing the availability of reuse spare parts (Wärtsilä, 2022).

Figure 8 below presents monthly availability figures for fuel pumps and fuel injection valves participating in the reuse parts programme. Two availability graphs are displayed, availability at the sales date and availability at the required sales date. Availability at the sales date measures the availability at the time when the sale was made, while the availability at the required sales date measures availability at the time requested by the customer. The latter is a later date, showing a slightly higher availability graph. The bar chart in blue presents units sold monthly. Both availability dates have fluctuated heavily recently, creating challenges across the whole spare parts organisation. Availability drops directly after the more extensive sale have been made. The organisation is continuously monitoring stock availability levels. The availability target for availability at the required date is set to 97 per cent for reuse parts (Wärtsilä, 2022).

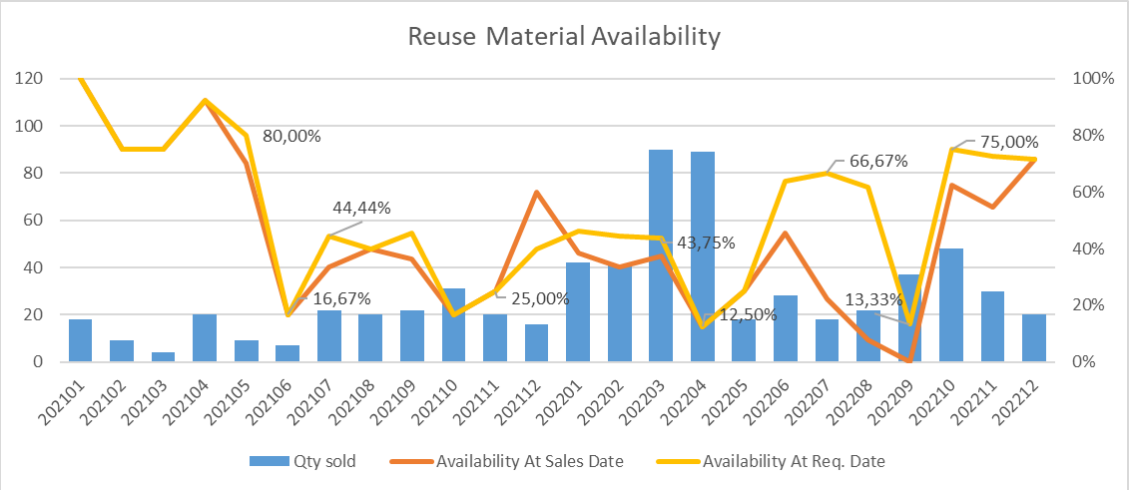

Figure 8. Availability monthly: reuse fuel pumps and injection valves (Wärtsilä, 2022)

4 Methodology

This chapter describes methods that were used during this study. First, the research strategy used is explained. Here also the criticality analysis method is introduced. This is followed by a description of the research data and how it was collected. The chapter is closed with data analysis methodology.

4.1 Research design and strategy

This study follows a qualitative research methodology and is explanatory in nature. According to Saunders et al. (2019, p. 179), qualitative research studies participants' understanding and relationships associated with the studied phenomenon. The eventual goal of qualitative research is to create a new conceptual framework or contribute to existing theory. Qualitative research supports on non-numerical data, where interviewing is a commonly applied data-gathering method. After data collection, data is often analysed using sorting and categorisation. Qualitative research types are many, out of which explanatory is one of them. Explanatory studies are looking to understand causal relationships between study variables. For example, explanatory research can focus on how certain variables affect a studied problem or phenomenon. Therefore, explanatory research questions commonly begin with "How" or "Why". Similarly, interview questions for data collection will likely start with the exact words (Saunders et al., 2019, p. 187).

This thesis uses a case study as the research strategy. Case studies are among the primary research strategies applied in qualitative research methodology (Saunders et al., 2019, p. 179). According to Yin (2014, p. 30), the case study strategy allows a deep study of a specific phenomenon in a particular context. At the centre of case study research is the need to understand how surroundings and study context are connected to the studied topic (Saunders et al., 2019, p. 196). Case studies provide the researcher with concrete and profound knowledge regarding a real-world topic. The potential fields of application are nearly unlimited since case studies are used across almost all scientific disciplines. Case studies have been used in, for example, business, social, and educational

research (Yin, 2014, p. 30). Similarly, potential subjects are broad. The case study can seek to gain an understanding of a person, organisation, or other real-world phenomena.

This research uses Process Failure Mode & Effect Analysis (PFMEA) tool to evaluate the criticality of found process challenges. PFMEA is a systematic approach to highlighting potential risks in products or processes (AIAG, 2019). The tool's strength comes from its capability to identify potential failure risks, observe possible causes, and explain what could result from a failure. The tool is commonly applied for manufacturing processes but has also proved helpful in other processes (Zhu et al., 2021). PFMEA analysis begins by cutting the case process into single process steps that will be analysed in depth (see Appendix 4 and 5 for finished PFMEAs). For each process step, the team performing the PFMEA defines potential failure modes. The potential failure mode is a presumption of something that can go wrong in the process (AIAG, 2019). Then, the team evaluates the potential effects of the failure mode. The potential effects are assigned with a severity number that ranges from very low to high (1 - 10) (see Appendix 2 for evaluation criteria tables). Next, the potential causes resulting in this failure mode are evaluated. As well here any existing cause prevention controls are listed. The existing prevention controls are given points on how well they prevent the failure mode. The scale runs from 1 – 10 (see Appendix 2). Thirdly, the tool analyses how well the current tools detect potential failure modes. Any existing detection methods should be listed and given a grade between 1 – 10 based on detection performance (see Appendix 2) (AIAG, 2019). After scoring severity, occurrence, and detection, the identified failure mode is given an action priority level to determine whether it requires actions from the management (see Appendix 3 for the action priority table). The range goes as low, medium, and high. The high AP failure modes require immediate action from the process stakeholders, while medium and low should have less urgency if high AP challenges have emerged (AIAG, 2019).

4.2 Data collection

The primary data for this study was collected using recorded unstructured and semi-structured interviews. According to Saunders et al. (2019, p. 437), unstructured and

semi-structured interviews are qualitative interviewing methods that explore participants' experiences, feelings and understanding of the studied subject. These allow the researcher to proceed to greater depths as the interviews are not bound to strict interview limits. The researcher can follow the participant's reply with a follow-up question that can reveal additional information. Semi-structured interviews allow similar flexibility in the interviewing situation. The main difference to unstructured interviews is that the researcher has a predetermined list of themes covered during the interview.

Table 1. Research Interviews

Interview no.	**Interview Date**	**Participant's job function**	**Interview language**
1. (PM1)	30.09.2022	Product manager	Finnish
2. (OP2)	15.12.2022	Operative purchaser	Finnish
3. (OP3)	16.12.2022	Operative purchaser	Finnish
4. (OP4)	19.12.2022	Operative purchaser	English
5. (SP5)	19.12.2022	Strategic purchaser	Finnish
6. (WF6)	21.12.2022	Workshop foreman	Finnish
7. (PE7)	03.01.2023	Process expert	English
8. (IP8)	03.01.2023	Inventory planner	Finnish

A total of eight one-hour-long interviews were conducted during this research. Table 1 above presents the conducted interviews and used interview language. The study participants were chosen so that all aspects, demand, supply and operations, of a CLSC could be covered. The interviews were guided using predetermined questions, while most of the interviews followed a format of unstructured interviews. Appendix 1 presents a general list of interview questions**.** This study offers direct quotes from conducted interviews. The author has translated the quotes from Finnish to English where necessary. Qualitative past delivery data supported the primary research data as a secondary source. The case company provided the data.

Interviews commenced with a manager responsible for the case company's reuse parts programme. The discussion provided valuable background information on how the current circular system operates. From here, the interviews continued to purchasing personnel responsible for ensuring a sufficient supply of reuse parts to meet customer demand. A total of four purchasing team members were interviewed with varying job functions and experience. The operative purchasers' primary responsibility in the reuse parts programme was order placement and management of open orders. Among operative purchasers, the purchasing role experience was spread as the most experienced operative purchaser had been working for 25 years, followed by nine years of experience and one year of experience for the newest team member. The fourth purchasing team member worked as a strategic purchaser. The strategic purchaser's function was noticed to carry more responsibility than the function of an operative purchaser. The strategic purchaser's primary responsibilities were securing a stable supply of reuse parts, product data management, and price negotiations. The person was also involved in strategic discussions with surrounding key stakeholders. The interviewed strategic purchaser had been working in the role for eight years.

After purchasing team, interviews proceeded with other stakeholders involved in the process. A workshop foreman overseeing the reuse part circular manufacturing operation was interviewed. The interviewee managed a group of three workshop workers. The foreman had long experience in the current role, while experiences among the workers varied from less than a year to multiple years. The following person interviewed was a process expert from the case company's sales organisation. The interviewee was responsible for building current sales side processes in the reuse part programme, creating necessary training materials, and giving training to sales personnel. The interviewee had good insight into the process flow from a spare part sales and core returns perspective. The person had been working in the role for four years. A final interviewee was an inventory planner. The inventory planner's primary responsibilities were to ensure that the case company had material available for sale while ensuring that stocks had a good rotation and that inventory costs were optimised. The inventory planner was regularly

involved in discussions regarding which parts and quantities were to be kept in stock. The interviewee had been working in the role for six years.

4.3 Data analysis

Acquired research data were analysed using a thematic analysis method with an abductive approach. According to Saunders et al. (2019, p. 651), thematic analysis helps the researcher to identify emerging themes and patterns by sorting findings into categories or codes. The analysis procedure depends on whether the research applies a deductive, inductive, or abductive approach. With the deductive approach, the researcher analyses the study results considering the existing theory. The purpose is to identify whether the current theory can be said to apply also in a new context that may be yet uncovered by research. Whereas the inductive approach aims to build new theories and frameworks based on the research data findings. Finally, the abductive approach is a hybrid of the approaches mentioned above, as the abductive approach aims to revise or further deepen the existing theory (Saunders et al., 2019, p. 641). The choice for the abductive approach can be motivated by the researcher's initial observations that there is more to a particular phenomenon than what is currently explained by the existing theory (Piekkari & Welch, 2019).

The analysis for this thesis began by transcribing each audio-recorded interview into a text format. Transcriptions were then screened, and findings were sorted into problem categories identified from the existing literature. As a part of the abductive analysis approach, these existing high-level categories were explored on a deeper level, contributing to existing theory by expanding it. The problem categories from existing literature can be found in the Challenges in circular manufacturing chapter. The challenge categories also provide the framework for the upcoming Results- chapter. The primary analysis phase was followed by PFMEA workshops to assess critical challenges in the CLSC. In these sessions critical and non-critical challenges were separated based on the PFMEA AP level (see Appendix 3 for the AP table). In this study, challenges ranked as high AP were considered critical and taken for further analysis.

5 Results

This chapter presents the results of this research. First, recognised challenges are listed as the result of a systematic identification process. A summary table of these challenges follows before closing the chapter with severity analysis with the PFMEA tool.

5.1 Recognised challenges

The interviews aimed to identify factors influencing demand and supply imbalance within the case company's CLSC. The performed interviews pointed to three sections in the case CLSC where the challenges took place: reverse supply chain processes, circular manufacturing ordering process, and circular manufacturing operation. The found challenges are presented by categorising them into challenge areas discussed in this study's theoretical background section. High-level areas are further divided into sub-categories.

5.1.1 Demand and supply challenges

Challenges relating to demand and supply management study the case company's CLSC system, how it was designed, and current efforts to balance demand and supply. It was observed that the current system was more demand-driven, and any purposeful attempts to balance demand and supply were made from the supply side.

Demand management

According to the Product manager (PM 1), the case company's sales personnel did not deliberately push or control reuse part demand, i.e., through marketing. A standard sales process was initiated by the end customer. The end customer requests a specific spare part with a part number that they looked up from a provided spare part manual. The spare part manual contains a part number for a new spare part; if available, a reuse part number is provided as an alternative. Ultimately, the customer chooses whether to buy new or reuse spare parts. The Product manager (PM 1) mentions that only a handful of spare parts have a reuse alternative since the business is still in its beginning phases.

It could be said that reuse part demand was managed with a reactive pull system. Once reuse parts were sold, this initiated supply-side processes. The demand for these parts was not pushed with tools such as demand forecasting, which would make the system more proactive towards the customer. Some study participants saw demand forecasting as a critical development direction since the reuse part volumes were anticipated to grow in the coming years (PM1). However, study participants ensuring the reuse spare part supply were uncertain whether this would be possible with the current process setup (OP 3; IP 8). An uncertain supply of cores was seen as the main factor prohibiting forecasting system implementation for reuse parts. In the current process setup, using a pull system to manage customer demand was not seen as problematic since more alarming issues were on the supply side. However, once the supply side improves, a forecasting system may be warranted to coordinate the system more efficiently.

Supply management – core recovery

This section explores the case company's core return strategy and how returns were motivated in the current system. In addition, any issues associated with these will be described. The case company had implemented a deposit-based return strategy to manage core returns from customers. The returned core was part payment for the reuse part (PM1). Therefore, timely returns were motivated with strict terms and conditions where the case company reserved a right to invoice the customer in case of a late core return. By purchasing a reuse spare part, the customer agreed to these terms.

The standard timeframe given for the return was 12 weeks. The timer started ticking when a reuse part was shipped from the case company's logistic centre to the customer (PE7). Therefore, the 12 weeks also included activities: new reuse part delivery to the customer and installation during maintenance. After the first six weeks, a reminder to return the core was sent to the customer. The case was closed if the core was returned to Wärtsilä's logistic centre within 12 weeks. When the core was not received within 12 weeks, a spare part sales team member would send another reminder to the customer mentioning that a penalty may apply if the core was not returned. Issuing a penalty was

always discussed with an account manager who was responsible for all sales projects with that specific customer (PM1). An invoice would be sent if the account manager gave the green light to penalise the customer for the late return. The amount invoiced depended on how many weeks late the return was. If the return exceeded 24 weeks, an invoice for the entire worth of the core was sent to the customer and the core was not expected back anymore.

Invoicing customers for late core returns was a hurdle for the case company. The Product manager described that while there have been many late return cases, only a portion of these has been invoiced while operating the current return system (PM1). The process was noticed to lack a disciplined approach, which leaves a possibility that after 24 weeks, the case company does not receive the core nor get compensation for it. The main concern was that invoicing the customer may hurt already established business relations. According to the Product manager:

> Penalty invoices for late returns have been waived off if the late return was caused by reasons not dependent on the customer. Or, if there was a big sales deal under negotiation with them, it was considered better to avoid bothering the customer with an additional invoice of minor value. (PM1)

Reverse logistic network

It was found out that the primary responsibility to return the core was on the customer's side. After the EOU core was removed from the engine, the customer was to package it into a provided box and ship it to the case company's logistic centre (PE7). In the current process, it was necessary to return cores to a single warehouse location in central Europe. Limitations in the current setup had already been recognised by the company as the Product manager (PM1) commented that a single point of return was a challenge in the reverse supply chain. One location increases process variables and logistics costs since the cores were returning worldwide. A preferable option would be to have a return location closer to the customer (PM1). The Process expert shared similar experiences:

> If we are talking about a customer based in Europe who needs to return cores to our central logistic warehouse in Europe, then everything is easy. The customer is likely able to return parts within the given timeframe. But we are a global organisation. This means that we are dealing with customers who are based on the other side of the ocean. In such a case, the return process evidently takes longer. (PE7)

Process expert (PE7) also raised concerns regarding reverse supply chain visibility. Since the customer took care of the return delivery, the case company had little information regarding when the cores might return. "*There are big issues with the return delivery because we cannot control what the customer does.*" (PE7). The purchasing team also mentioned the lack of information on returning cores (OP2; SP5). The information regarding returning cores was seen as valuable for the purchasing team.

5.1.2 Information and knowledge challenges

Many study participants named challenges relating to information and knowledge among the most influential hampering the process performance. This chapter explores challenges observed in internal and external process knowledge.

Internal process knowledge

It was found that some of the CLSC process issues could be traced back to internal process knowledge. Mainly this was noticed to disturb the spare part sales team's reverse supply chain processes for core returns. The Product manager and Process expert (PM1; PE7) estimated that the rate of core returns could be hindered due to stakeholders not being fully aware of the nature of reuse parts and what kind of processing is needed. The product manager emphasised:

> One of the challenges is to create an understanding internally and towards the customer that when a reuse part is sold, the core must be returned within the given schedule. Otherwise, there will be a fine as per order conditions. (PM1)

The Product manager (PM1) continued that, as the reuse spare part sales volumes are only a small piece of the case company's entire spare part business, a normal salesperson might deal with reuse spare parts perhaps a couple of times per year. Since people are often not involved with the process, the steps may be forgotten. Process expert (PE7) added that spare parts sales organisation has many instructions and exceptions that should be considered. The case company also had an old parallel reuse part process still in place, which was said to complicate processing, as the sales personnel were not always certain which process should be followed and communicated to the customer. The Process expert (PE7) emphasised that the spare parts sales personnel are an organisation with around 250 members where each person has a specific customer market area globally—as a result, spreading knowledge and understanding in such an organisation is tricky since "*whenever you are dealing with plus 200 people. It is always difficult to implement new processes, and the learning curve is slow. Especially when you think a person might be handling this kind of case twice yearly, perhaps.*" (PE7)

Some level of process knowledge issues was also observed in the interviewed purchasing team. The respondents reported that process responsibilities and agreed ways of working with the reuse parts were not always clear (OP3; OP4; IP 8). The interviewed Strategic purchaser (SP5) commented that any ordering process issues started already when the reuse part process was initially released. When the current process was developed, there was no purchasing team presentative to ensure that the purchasing team's needs would be considered. The Strategic purchaser commented:

> My feeling is that none of the purchasing department's process developers was involved in the development of the current reuse part process, even though the purchasing team has a clear part to play in it. Therefore, any issues that purchasing may face have gone undiscussed. Until now, the process has been coordinated by the spare part sales process development (SP5).

Customer process knowledge

There were concerns about whether customers were fully aware of how to deal with reuse spare parts (PM1). These issues would be closely connected to spare part sales personnel's process knowledge, as sales were the first point of contact for the customer. The limited customer process awareness was expected to contribute to reverse supply chain challenges, as the customers had a significant role in the return logistics. Process expert (PE7) was doubtful if customers fully acknowledged the terms and conditions in force when they decided to purchase a reuse spare part. The Process expert explained:

> If the spare part sales personnel send the general terms and conditions via e-mail, you cannot take it for granted that the customer will read it. So, you cannot say that you have informed the customer. You cannot force the customer to read everything you send him. The communication part is always the trickiest, especially when you are dealing with customers. (PE7)

The Product manager (PM1) explained that the already mentioned newness of the reuse spare part business also impacts customer process awareness, as it does for internal process knowledge. The fact that the core must be returned can be new to some customers. Additionally, hundreds of spare parts can be replaced in an engine during standard maintenance. Therefore, the returnable core can go unnoticed if the customer does not know to pay focus to it (PM1).

The lack of process knowledge concretises at the case company's logistic centre. One clear sign is late returns, but the cores have also been noticed to return in varying conditions and packaging, even though the case company provides instructions on how the parts should be returned (PM1; SP5). Customers were also required to include appropriate product documentation to the return delivery that tells the logistic centre inbound personnel what is in the box (PE7). Cores returning without proper documentation were causing significant issues at the case company's logistic centre:

> Our customers are returning cores without proper documentation. This is causing many issues, especially in the inbound. Without documentation, we are not able to track what is in the box. So, this means that we are wasting a lot of time and resources trying to understand what we just received in this delivery. The customer should attach a label to the return that helps us to identify it, but the reality is that the customers are not doing it. (PE7)

5.1.3 Material flow challenges

The material flow challenges investigate how finished reuse products, cores, and sub-components flowed in the case company's process. The chapter also reviews challenges associated with seeding practices and issues resulting from inventory management.

Circular manufacturing order creation

According to the Operative purchaser (OP2), the ordering process for reuse parts starts when the stock balance has gone below pre-set safety stock level. As a result, the company's ERP system calculates the shortage and creates a purchase requisition for operative purchasers to process. The purchase requisition indicated that operative purchasers need to order something to replenish the safety stock deficit. After opening the reuse part purchase requisition, the order creation process began by checking if enough cores had returned from the field. If cores are available, the operative purchaser places a circular manufacturing order and ships cores to the operating facility. If enough cores were not available, the operative purchaser put the order on hold until enough cores had returned (OP4). Nearly half of all reuse orders were put on hold due to missing cores during the past years (see Figure 9). If an order had been put on hold due to missing cores, the time spent waiting until order placement was 36 days on average when considering all five reuse parts in this study. This had a significant contribution to the total lead time of reuse parts. Figure 10 below presents the number of orders during 2021 – 2022 and the average waiting times per reuse part type. The long waiting times were concerning to all purchasing team members.

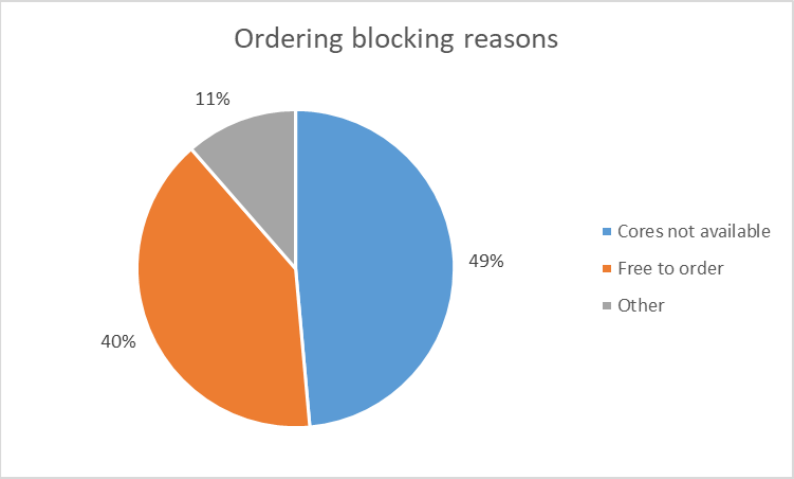

Figure 9. Ordering blocking reasons from 2021 – 2022

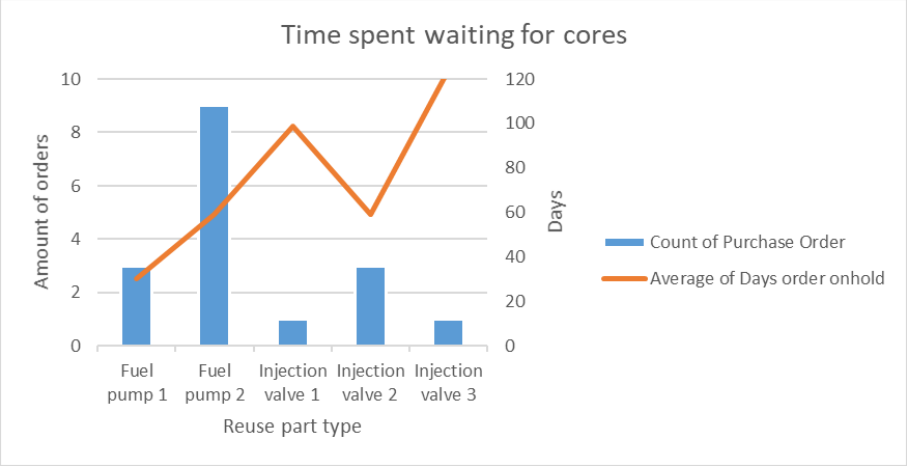

Figure 10. Time spent waiting for cores from 2021 – 2022

It could be said that in the current ordering process, the reuse part supply stops when cores are not available. This was problematic as customers were promised reuse spare parts with a quoted lead time (OP3). The purchasers were questioned on what happens when there are no cores available. The Operative purchaser emphasised that *"it is unclear what should be done if we have no cores available and reuse part stock is empty. Right now, we block the purchase requisition and wait for more cores to return"* (OP3).

Core inventory management

It was observed that core return rates varied among reuse parts. Based on orders put on hold due to missing cores during 2021 - 2022, reuse fuel pumps were more often facing a situation where there were not enough cores to send for circular manufacturing (see Figure 11). During this period, a third of all reuse injection valve orders were waiting for cores, while for reuse fuel pumps, the figure was double, as two third of all orders were waiting for cores. The pain point within the two reuse fuel pumps was especially fuel pump 2. This was estimated to result from the nature of these products. The reuse injection valve could go through three circular manufacturing cycles, while reuse fuel pumps only one cycle before disposal. As a result, the total amount of reuse injection valves in circulation is much higher than in reuse fuel pumps (PM1).

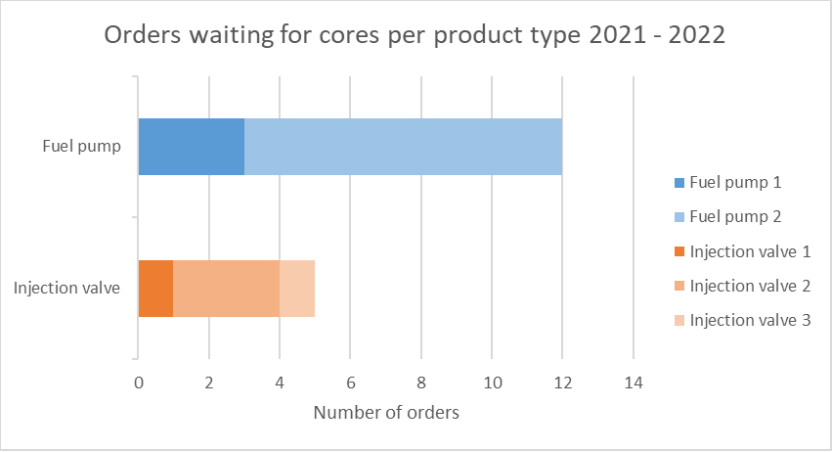

Figure 11. Orders waiting for cores per product type 2021 – 2022

Occasionally, more cores were available than the demand for reuse parts at that moment. In this case, the company had no policy determining what to do (OP3). An Operative purchaser had observed the situation and saw there a possibility for improvement:

> What should we do with excess cores that do not have demand right now? Why don't we just send those also for circular manufacturing, even if our reuse part stock level would go above the set safety stock? It would be better to have those parts in stock as finished reuse parts rather than as cores. (OP3)

Order lot sizing

It became apparent that reuse part order lot sizes were not managed adequately across all case parts. The order lot size was determined based on core availability during ordering (OP2). If there were a need to place a reuse part order, for example, for 20 pieces and enough cores were available, operative purchasers would send all 20 pieces for circular manufacturing. Similarly, there was uncertainty regarding the minimum reuse part order quantity. If only three cores were available, an order for this quantity was often placed. The Operative purchaser (OP2) mentioned, "*it is not clear what is the minimum order quantity per reuse part order*".

Orders placed with too low quantities could be expected to increase logistics and handling costs per unit. While too high amounts were causing concrete issues at the internal workshop. The Workshop foreman (WF6) emphasised that the workshop has limited space for intermediate storage. Therefore, too large core shipments disturbed the workshop's operations. A well-manageable lot size would be 12 pcs (WF6).

Sub-component inventory management

Global supply chain challenges impacted the case company's supply for sub-components. Respondent reported that sub-component lead times had drastically extended after the COVID-19 pandemic, which pressured the company's operations (OP3). Additionally, it was noted that required sub-components for internally produced reuse parts suffered from outdated inventory management practices. The main issue was that some of the regularly needed sub-components were not kept in stock and had to be ordered separately for each new reuse part order. Which, as a result, increased the total lead time. It was also found that sub-components already held in stock needed safety stock level adjustments to better support the current level of demand (SP5). As a part of the issue, a few reuse parts' product structures were not up to date, which resulted in the issue that the company's ERP did not reserve required sub-components when it was time to order reuse injection valves. At the time of the interview, the responsible strategic purchaser

had already become aware of the issues and solutions that were being looked for. The Strategic purchaser saw the situation as follows:

> We have been battling with low stock availability for reuse part sub-components. This has to do with the fact that some of the components have not been stocked using safety stocks. However, this should improve as we have started to update the reuse injection valve bill-of-materials and manage sub-components with safety stocks. This should help in managing sub-component inventories. (SP5)

Balancing supply with seeding

Using a deposit-based return strategy for core returns requires the company to supplement the reuse part supply with new components to ensure sufficient stock availability. This originates from the stochastic nature of core returns. According to purchasing team members, there was no organised process to transfer new components into the reuse part stock. Some transfers had been done to create an initial inventory for a new reuse spare part or if there was an urgent customer order with much pressure from the spare part sales team (IP8; OP2). In case of an urgent order, the Operative purchaser would approach the responsible strategic purchaser with a request whether new products could be transferred into the reuse part inventory. Although, there was no coordinated approach to this, as respondents mentioned that it was not clear in which cases the transfer should be done (OP3). The interviewed Inventory planner highlighted the issue in the current way of working: *"Now we are transferring new parts to reuse stock sometimes, but it is unclear when it should be done and who is the end responsible for deciding whether a transfer is needed."* (IP8)

The possibility of supporting reuse part stock availability through seeding was further complicated for both reuse fuel pump types due to a material replacement process. According to the strategic purchasers (SP5), both original fuel pump variants had been replaced by a newer product version. This prohibited the case company from transferring

new pumps into the reuse stock since it preferred not to mix different product versions. The ongoing replacement process was found to disturb the reuse fuel pump supply.

5.1.4 Core challenges

Any issues observed in the interview data connected to the handling and management of cores are presented in this chapter. The chapter begins by describing issues arising from the core acquisition. Core quality management practices follow this. The topic is closed with a sub-chapter on core version management.

Core acquisition

The case company had no alternative sources to acquire cores than their customers. The components in the reuse part programme were unique in the sense that the components were designed either by the case company or in close collaboration with a supplier (PM1). This took away the possibility of using third-party sources for core acquisition. While the lack of external sources was partly a limiting factor, the situation had strategic benefits as the case company could have more control over their spare part business (PM1).

Core quality control

As in any CLSC system, the case company's cores also returned in varying conditions after customer use (SP5). It became apparent that there were currently limited measures to filter out too worn cores when receiving them in the logistic centre. When a core returns to the warehouse, a check is done to confirm that the material number corresponds with the part that is being stocked. During the check-up, cores that have visible damage by visual inspection, i.e., cracked frame, can be removed from the cycle. However, there was no process to check for less visual damage that might indicate that the core is ready for disposal. Nor does the inbound centre personnel check how many times the core has already gone through the cycle. Reuse spare parts have a marking telling how many times those have been circular manufactured (PM1).

There have been a few occasions when broken or otherwise, EOL injection valve cores have reached the workshop (WF6). The workshop personnel then disposed such cores. Too degraded cores that reach workshops hinder the reuse product delivery as the workshop must under-deliver or ask to send more cores to process. The Product manager (PM1) acknowledges the challenge of returning core condition evaluation at inbound. According to the Product manager:

> There is currently no process in place to check the overall condition or markings on returning cores. The warehouse inbound personnel could be instructed to remove cores with disposal indicating markings on them. Deeper condition evaluation requires more technical understanding, which is currently not available in the logistic facility. (PM1)

Core version management

As mentioned in one of the earlier chapters, the reuse fuel pumps underwent a version change (SP5). The case company faced a challenge of whether older type cores should be updated to a newer spec. According to the Strategic purchaser (SP5), the returning older version fuel pump cores can be updated to the latest version. However, this would come with a cost since one of the priciest sub-components requires changing. Therefore, the company had to estimate whether the update was worthwhile economically. The other possibility weighed was to create a new reuse fuel pump type to keep two versions separate (SP5). This would result in additional reuse products, which would require more follow-up. Also, this was estimated to create a question of which customer installations can and are willing to use older type reuse fuel pump when a newer would be available.

5.1.5 Operational challenges

After order creation, the case company's purchasing personnel shipped cores from the logistic facility to an external supplier or internal workshop for circular manufacturing. This chapter describes any reported problems in the circular manufacturing operation.

Circular manufacturing process challenges

According to the study respondents, circular manufacturing order lead times had extended from month to month. Long lead times were observed with both suppliers, the external supplier and the internal workshop. Figure 12 presents the past lead time for reuse fuel pumps coming from the external supplier. According to an Operative purchaser (OP3), the supplier's overall lead times have extended over the past years. This was due to the challenging global supply chain situation and production capacity constraints due to higher-than-normal demand across the supplier's whole offering. Yet still, the supplier has continuously delivered reuse fuel pumps faster than the "LT agreed" in 2022. More concerns were raised for reuse injection valves coming from the case company's internal workshop (OP4). The internal supplier's lead times were continuously noticed to exceed the promised lead time since May 2022 (see Figure 13). The blue bar "LT agreed" depicts the agreed lead time and is managed by the Strategic purchaser. The aim was to maintain as accurate lead time as possible in the system since the same lead time was provided to the end customer when buying a reuse spare part (SP5). Therefore, LT agreed shifts throughout the year. Based on this analysis, it could be concluded that more alarming issues were at the internal workshop.

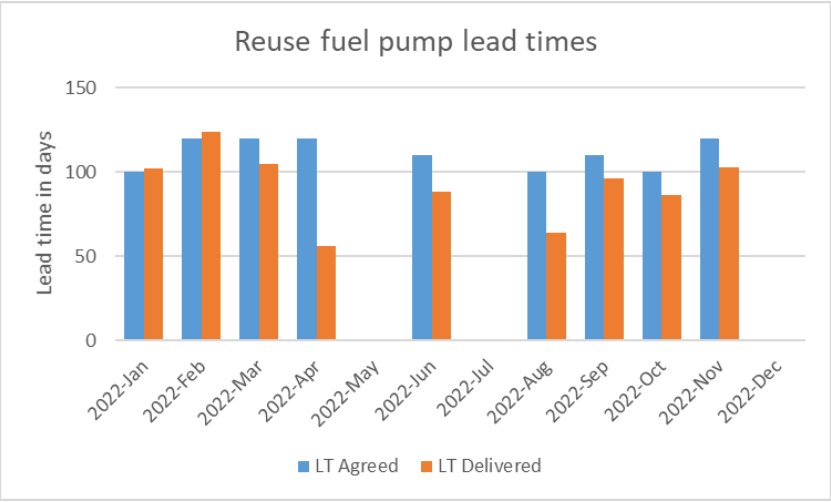

Figure 12. Reuse fuel pump lead times, external supplier

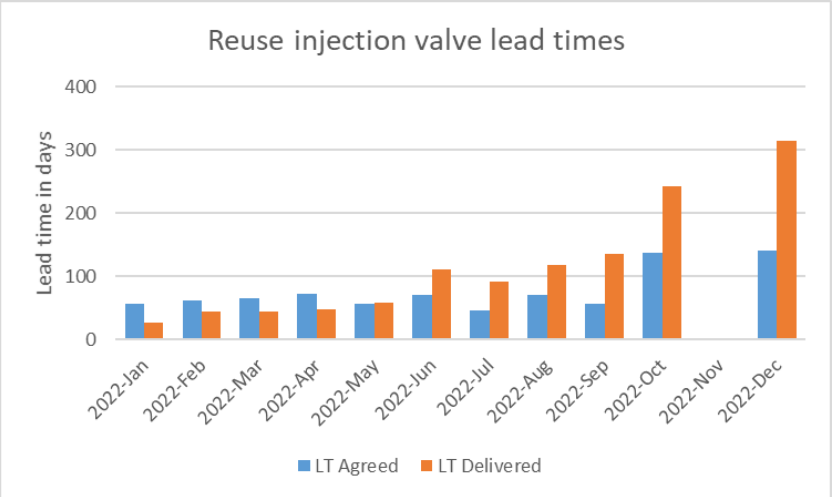

Figure 13. Reuse injection valve lead times, internal supplier

The Workshop foreman (WF6) was questioned about the current delivery performance. According to the Workshop foreman, the global supply chain challenges were the main cause of long lead times. The Workshop foreman explained that "*we are ordering needed sub-components per each order. We cannot hold these sub-components in stock. Since our suppliers deliver sub-components with longer lead times, this naturally extends reuse injection valve lead times*". (WF6)

The global supply chain challenges slowed operations through extended sub-component lead times. However, more alarming findings were that the workshop ordered all required sub-components on a buy-to-order basis and could not hold any stock. The required sub-components were ordered from the company's warehouse in central Europe. Ordering sub-components only after receiving the circular manufacturing order significantly increased the total lead time. Otherwise, the Workshop foreman (WF6) did not report any issues in the circular manufacturing process where cores are, i.e. cleaned, disassembled, reassembled, or packaged. (WF6). It was pointed out that if the workshop had all required sub-components available, it could reach a two-week throughput time for a 12-piece set of reuse injection valves (WF6). When considering this and the lead times in Figure 13, the sub-component lead times and the lack of inventory management practices were the main contributors.

The internal workshop was also noticed to have other duties. There were a variety of jobs coming directly from customers. All incoming orders were served first-in, first-out basis (WF6). The workshop did not have a dedicated capacity planning system in place. When the number of direct customer orders was high, the available capacity for reuse part orders was lowered (SP5). However, the Workshop foreman (WF6) pointed out that the workshop can be agile by shifting the sequence of work orders if one order becomes urgent. The prioritisation, though, requires that all necessary components are available. Based on this, the capacity was not seen as an issue with the current level of demand. However, the limited number of circular manufacturing locations could become a capacity constraint if volumes suddenly increase (PM1).

5.2 Summary of recognised challenges

Table 2 below summarises identified challenges in a single view. Found challenges were shared into five high-level categories: Demand and supply challenges, Information and knowledge challenges, Material flow challenges, Core challenges, and Operational challenges. Each challenge category consists of sub-challenge categories identified during this research. These are shortly described in the right-hand side column.

Table 2. Recognised challenges

Recognised challenges	**Description**
Demand and supply challenges	Challenges arising from the current efforts to balance demand and supply
Demand management	*No direct challenges. Reuse part sales were initiated by the customer / pull system.*
Supply management – core recovery	*The core return monitoring was not followed through, which resulted in a problem that unreturned cores could go without reimbursement.*
Reverse logistic network	*A single global core return point was a problem for returns. The company also lacked visibility on how and when the customer returns cores.*

Information and knowledge challenges	Challenges arising from limited process knowledge
Internal process knowledge	*The internal stakeholders were not necessarily aware of the reuse spare parts and the type of processing required.*
Customer process knowledge	*Customers were not necessarily aware that cores must be returned. The customer might have also returned cores in too bad condition or without appropriate return delivery documentation.*
Material flow challenges	Challenges arising from current ordering and inventory management practises
Circular manufacturing order creation	*Orders were created reactively after a customer order or once safety stock was too low. Also, much time was spent waiting for cores.*
Core inventory management	*Core return rates varied between reuse product types, and the case company did not have a policy regarding excess cores.*
Order lot sizing	*Some reuse spare parts were missing minimum and maximum ordering lot sizes. Unoptimised lot sizes disturbed operations.*
Sub-component inventory management	*Global supply chain challenges extended delivery lead times. Plus, some of the regularly used sub-components were not held in stock, or the defined safety stock level did not support the current demand.*
Balancing supply with seeding	*The purchasing team was missing a coordinated approach to replenishing reuse part stock with new components (seeding).*
Core challenges	Challenges arising from the management of cores
Core acquisition	*The only source for cores was customers.*
Core quality control	*Occasionally, too degraded or otherwise EOL cores proceeded to downstream processes when those should have been disposed.*
Core version management	*Revision changes in reuse parts disturbed part supply temporarily.*

Operational challenges	Challenges observed in the circular manufacturing operation (external supplier and internal workshop)
Circular manufacturing process	*No challenges were observed in the operation itself. Long lead times resulted from reactive sub-component procurement, and that the workshop could not hold any inventory.*

5.3 Analysis of criticality

To identify the most alarming challenges from the ones mentioned in the previous chapter, a severity analysis with the PFMEA tool was performed. Three problem sections of the case CLSC, reverse supply chain processes, circular manufacturing ordering process, and circular manufacturing operations were laid out and each process step with associated challenges was examined with the company professionals. One PFMEA session was organised regarding reverse supply chain processes with spare part sales personnel, a Product manager and a Process expert. Another session was organised regarding the circular manufacturing ordering process and circular manufacturing operations with purchasing personnel, Strategic purchaser, Operative purchaser, and Inventory planner. The decision to do separate sessions was taken since the two groups were not involved in each other's processes. Out of the challenges in Table 2, some of the challenge categories were left out of the criticality analysis if no significant challenges were observed or the challenge was not regularly observed in the CLSC cycle. As a result, challenges relating to *demand management* were left out of the analysis. The current pull system to manage customer demand was not seen as a major issue in the current process setup, where supply could not keep up with demand. This could, however, become an issue once the supply side picks up. Additionally, *core acquisition* and *core version management* were left out of the analysis. Regarding the *core acquisition,* customers being the single core source was seen as problematic, but at the same time, as a feature of the case CLSC since customers were the only potential core source. Therefore, the challenge was not seen as a potential critical challenge. The study participants acknowledged challenges in *core version management*. However, this challenge surfaced only when a reuse part received a version change. Therefore, the issue did not appear in the daily CLSC

cycle and was therefore considered not as a potential critical challenge. Final PFMEA tables can be found in appendices 4 and 5.

Critical challenges with high AP were observed from four challenge categories in reverse supply chain processes. The first two critical challenges belonged to the categories of *internal process knowledge* and *customer process knowledge.* The study participants saw poor customer process knowledge to be the cause of many of the return process failure modes (see Appendix 4). Since the customer's first point of contact was spare part sales, the internal process knowledge was seen as the source for this, ranking it also as critical. The second high AP challenge belonged to the *reverse logistic network* – category as the case company lacked visibility on customer core return behaviour. In the PFMEA analysis, the lack of visibility is not written as a cause to any of the potential failure modes. The criticality of lack of visibility became apparent through discussions and high Detection numbers for potential failure modes occurring during customer core returns. The high Detection numbers resulted since the company had no visibility on customers' doings, therefore, no tools to detect the issue before it happened. The final high AP critical challenge belonged to the *supply management – core recover* category. An undisciplined approach to late return penalising was seen as a critical issue since it created a possibility that the company might be left without a returned core or compensation in case a core was not returned or returned extremely late. The internal process knowledge was expected to be the primary root cause of this issue.

Some essential challenges were ranked as AP-level medium. The first medium-level challenge had to do with customers returning cores without including delivery documentation in the return delivery. This was expected to result from the limited *customer process knowledge*. The second medium-level challenge was under the challenge category of *core quality control.* The fact that the company was missing a structured process to filter out too worn-out cores was as seen as an issue with a somewhat effect on downstream processes. The final medium AP challenge resulted from the current *reverse logistic network* design. The case company's single location for returning cores was seen as

problematic, especially when customers were sending back cores from outside Europe. The difference between high AP and medium AP was that the cores were still flowing in the process with medium AP challenges, though with limited performance, whereas high AP challenges could result in lost cores.

In the PFMEA session with purchasing personnel (Appendix 5), the first high AP-ranked issue had to do with *the circular manufacturing order creation* challenges. The fact that orders could not be placed if the team did not have enough cores available was an issue as it expanded the total lead time. However, this was out of purchasing's hands to influence since the sales personnel were responsible for securing timely core returns. In terms of fulfilling customer demand, the following high AP ranked challenges were the reactive nature of the case company's ordering process and the fact that there was no policy to determine actions for excess cores. A reactive ordering system was observed with *circular manufacturing order* challenges, while the missing core inventory policy resulted from the current approach to *core inventory management*. The following high AP challenges were observed in the *circular manufacturing process* as sub-components were ordered only after the circular manufacturing order was created. S*ub-component inventory management* practises had a role to play since the sub-components were ordered from the company's warehouse. The issues with sub-component management resulted in long circular manufacturing order lead times, which significantly limited reuse part availability. The final high AP-ranked issue resulted from the current efforts to *balancing supply with seeding.* There was no structured process for transferring new components to reuse stock. In the case CLSC, this was identified as a critical process element.

Issues with medium or low AP priority were also identified. Low AP priority challenges resulted from *order lot sizing.* The challenges with lot sizes were not seen as critical since the goods were still flowing in the process, and this was reported to result in only minor harm. Global supply chain challenges' impact on *sub-component inventory management* was seen as a medium AP level challenge. For this and the low AP priority issues, the purchasing team already had some tools to mitigate the impact.

6 Discussion

This chapter examines the study results and discusses them with existing literature. As well the chapter provides improvement proposals for the case company's most critical challenges. This research aimed to identify factors contributing to unbalanced demand and supply in a CLSC, the most critical factors, and how a company could improve the situation. To realise this purpose, three initial research questions were drafted: "*Why reuse spare parts are often suffering from a poor balance between demand and supply?", "What are the most critical issues regarding demand and supply balance?",* and *"How should the CLSC be improved to secure a better balance of demand and supply?"*.

In total, 14 different challenge categories were identified from the conducted interviews that could be expected to contribute to demand and supply imbalance. A detailed summary of challenge categories can be found in Table 2 on page 54. The study revealed that the case company had not experienced demand management problems. No overstocks of reuse parts were reported. Observed challenges were mainly at the supply side of the CLSC, as the reuse spare part supply could not keep up with the current level of demand. Challenges were observed across the case CLSC and its stakeholder groups, spare part sales, purchasing, and circular manufacturing operations. The process challenges within the spare part sales team and reverse supply chain processes presented themselves as uncertainties in quantity, quality, and timing of core returns. Multiple issues were identified that contributed to the current situation. At the core, these issues resulted from limited process knowledge and the current design of reverse logistic processes. Challenges observed with the purchasing personnel in the circular manufacturing ordering process and circular manufacturing operations resulted in reuse part stockouts and long lead times. These issues could be expected to result from poor core availability by quick observation. The study, though, also revealed other contributing factors. On top of poor core availability, most supply challenges resulted from the reactive ordering system, outdated sub-component inventory management methods, and missing seeding strategy. Regarding the actual circular manufacturing process at the internal workshop, no issues

in the operation itself were identified. This was surprising as the operations are often described as complex and challenging (Duberg et al., 2020; Kurilova-Palisaitiene, 2018).

6.1 Theoretical contributions

This study contributes to existing theory by providing novel information on the criticality of demand and supply balance issues. The criticality of these CLSC issues has not been assessed earlier. Additionally, this study highlights the added importance of internal and external process knowledge in a CLSC system. Finally, the study points out the relevance of a coordinated seeding strategy in a CLSC with single source products.

This study found that the limited internal and external process knowledge significantly impacts the performance of a fast-paced spare part CLSC. Primarily, this was noticed to affect the reverse supply chain process. It was seen as plausible that internal stakeholders and the end customers were not fully aware that the reuse parts required returning. Contrary to this research, Schenkel et al. (2019) did not identify CLSC process issues resulting from poor process knowledge when studying CLSC value creation constraints with four case companies. The difference could be expected to result from many factors. The case companies in Schenkel et al. (2019) study were all using credit-based return strategy to manage cores back from the customers. The customers were credited a certain amount when the EOU core was returned. This credit could then be used for new purchases. The credit-based return strategy has been widely applied in a CLSC, and the credit is seen as a strong incentive for the customer to return the EOU core (Goltsos et al., 2018; Schenkel et al., 2019; Östlin et al., 2008). Whereas the case company of this study used a deposit-based return strategy to manage customer core returns. Deviating from the deposit-based strategy presented by Östlin et al. (2008), the case company's customer was supposed to return the core after receiving the new reuse part. According to Östlin et al. (2008), the EOU core is returned first to get a new reuse product in their deposit-based strategy. The case company's approach allowed customers to minimise engine downtime since the EOU core was removed after the new replacement part was delivered to the site. While the current return strategy supported

customer operations, it created the need for additional process knowledge and follow-up to get the EOU cores back from customers. The case company's respondents explained that Wärtsilä had experienced with other return strategies. The company used to repurchase cores from customers. This was though found to as noncompliant legally, which led to the introduction of the current returns management system. The case company's return strategy could be effective when working at full potential, resulting in a returned core or a reimbursement for a lost core.

The fact that the case company's reuse part process was still new and small in size created the need for the creation of initial process knowledge. Schenkel et al. (2019) estimated that since their case companies had already been actively involved in CLSC business, the companies had already become acquainted with the process. Therefore no process knowledge issues were identified. Another factor was that the case company used the same forward and reverse supply chain processes for reuse spare parts and standard new spare parts. This allows the company to achieve efficiency through economies of scale but risks that the returnable product can get lost in the mass of standard spare parts. Additionally, this setup requires that the internal stakeholders are aware of the reuse parts and the need for added follow-up. In the study of Schenkel et al. (2019), two OEM case companies handled the reverse supply chain internally, while the other two used sub-contractors. The two OEMs handled reuse parts separately from other operations by having separate business units and recovery departments for reuse products. This could be expected to contribute positively to process knowledge but, simultaneously, requires that the reuse part business has reached a certain level of volume that supports these operations.

This research observed that in the case company's fast-paced CLSC with unique products, a seeding strategy is a must to secure balanced demand and supply environment. Östlin et al. (2008) point out that when a company uses the deposit-based return strategy, like the case company, seeding of new components is a vital source for reuse parts. However, seeding is not widely covered in the literature. It is mainly used during product

introduction to create a seed stock rather than as a continuous tool to support circulation during the product's lifetime (Abbey et al., 2019; Östlin et al., 2008). The need for a seeding strategy arises because the company does not have other sources for cores, and the timing of returning EOU cores is uncertain. Much time was spent waiting for cores in the case company's current operations, disrupting reuse part supply and eventually leading to gaps in the return flow of cores. This is the main challenge of a CLSC since forward and reverse flows need to be in balance to avoid process disruptions due to missing materials (Schenkel et al., 2019). In a circular process, reuse parts must be sold to get cores. Therefore, seeding can help maintain a steady process flow.

Earlier literature has examined factors contributing to CLSC system demand and supply imbalance. For example, Kurilova et al. (2018) presented challenges observed in remanufacturing CLSC literature, Goltsos et al. (2019) provided a view on CLSC and core return challenges, and Schenkel et al. (2019) studied challenges disturbing CLSC value creation. When looking at the identified critical high AP challenges, besides above mentioned, most of them have been observed in CLSC literature. Issues associated with return visibility and uncertain timing of returning cores could be among the most noted CLSC system challenges. Such studies as Abbey et al. (2019), Goltsos et al. (2018), Kurilova et al. (2018), Steinhilper & Butzer (2019), and Wei et al. (2015) name it as a significant obstacle in a CLSC. Similarly, poor core availability has been identified as a central performance limiting factor. In the study of Kurilova et al. (2018), all four studied case companies suffered from a lack of core material for remanufacturing. Regarding reuse product manufacturing strategies and whether to use pull or push manufacturing, the literature has identified that an unfitting manufacturing strategy can result in extended lead times and therefore limiting reuse part supply (Jia et al., 2016; Takahashi et al., 2012). Poor inventory management practices have also been identified to disturb CLSC operations. Kurilova et al. (2018) and Zhu et al. (2014) observed that unoptimised inventory management practices contributed by extending reuse part production lead times.

6.2 Improvement proposals for the case company

Below discussed improvement proposals would result in more balanced demand and supply in the case company's CLSC process. Some of the improvement proposals are easier to implement than others. For example, designing a seeding strategy or bringing inventory management practices up to date should not require organisation-wide transformation. Whereas the creation of process knowledge across the organisation and external stakeholders is something that takes time and effort to achieve.

Process knowledge in a multinational organisation is a large topic and would need a whole new thesis on its own. Therefore, here are only some observations that could help the organisation better spread the knowledge regarding reuse parts. First, the case company's CLSC could benefit from creating a recognisable brand for the reuse parts. By recognising the brand, customers and internal stakeholders could be expected to be more aware that the part must be returned after use. This is not an original idea, as some companies have branded their reuse products to create awareness. For example, Caterpillar has branded their remanufactured parts as Cat Reman – parts (Caterpillar, 2022). Other examples to mention are the American agricultural machinery manufacturer Case IH and Finnish forestry machine company Ponsse who both advertise their remanufactured parts as Reman-parts (Case IH, 2021; Ponsse, 2021). Another opportunity for the case company to increase process knowledge would be to start knowingly spreading information about the reuse parts. A possible outlet could be an intranet page or a published white paper. Similarly, the case company could set up a website for its customers where they can get information on the reuse parts along with the latest return instructions and return delivery labels. Finally, it could be beneficial to create some separation in-between new spare part supply and reuse part supply to better highlight the return requirement of reuse parts at EOU. A first step could be to define sales personnel responsible for the reuse parts, therefore creating a sort of expertise centre. If the reuse spare part business grows enough, a separate business unit and return facility with designated processes could be warranted.

The visibility and better estimation of returning cores remain as a challenge in all CLSC systems (Ambilkar et al., 2022). As described in the theoretical background section researchers have proposed forecasting systems to estimate the core arrival better. Depending on how the return network is constructed, the core return is still subject to multiple variables, making it difficult to predict the exact time of the return (Schenkel et al., 2019; Wei et al., 2015). Researchers have proposed providing returnable products as a service to customers. The seller has a better view on core returns since they maintain ownership of the product (Matsumoto, 2019). The products-as-a-service system may prove beneficial in some CLSCs, but it does not fit everywhere. In the case company, servitisation of the reuse parts would not solve the issue with return timing since the customer still would need to package and ship the core to the logistic facility in the current process setup. However, it could be expected that when the volume of reuse parts in circulation increases, the need for detailed return information reduces as the tempo of returning cores grows more stable (Schenkel et al., 2019). This would allow the company to build some inventory on cores, alleviating some of the pressure from core return visibility.

The current pull circular manufacturing ordering process significantly tilted the demand and supply balance since the purchasing team was often found in a situation where it could not fulfil the customer demand. The purchasing team should consider changing to a push ordering strategy to be more proactive towards customer demand. Jia et al. (2016) investigated demand and supply imbalance in remanufacturing CLSC and concluded that changing between push and pull strategies depending on the reuse product's lifetime status can provide good results in satisfying the demand and optimising the process performance. The push strategy was used at the beginning of the lifetime as the customer demand was high, and it was crucial to manufacture returned cores into reuse products as soon as possible. Once the reuse product's lifetime status had reached post-maturity, with demand starting to drop, the production strategy was changed to a pull strategy. Therefore, producing just enough reuse products to meet the customer demand while limiting costs and excess stocks (Jia et al., 2016). The similar setup could be fruitful in the case company's operations. The push production strategy should be put

in place for products which are expecting growing demands. For the case company, this would mean demand forecasting. When products have reached the maturity phase, with the plateaued or downward-facing demand curve, a pull strategy should be considered. The use of the push strategy requires a stable flow of cores. Therefore, the core supply has to be secured before opting for this strategy (Jia et al., 2016).

To shorten circular manufacturing lead times and as a result meet customer demand more effectively, the company should review the current inventory management practises for reuse part sub-components. The main point would be to start storing products with safety stocks and to update any current safety stocks that do not support the current level of demand. The case company was noticed to have a structured way of managing new component inventories, however, the reuse part sub-component inventories had gone unmanaged, or the practices were being developed. Overall the management of reuse parts within the purchasing organisation could benefit from a designated person whose responsibility would be to coordinate inventory management activities and bring together the key stakeholders for strategic decisions. Some development was already observed regarding inventory management practises as the reuse product bills-of-materials had been updated, which helped reserve required sub-components for each circular manufacturing order. The company also planned to start sending all required components with the EOU core to the workshop, which could be expected to cut down the total lead time as the workshop does not purchase sub-components only after order receival.

To better fulfil customer demand and create a more stable flow of parts in the reuse process, the company should plan a more structured approach to seeding, replenishing reuse part stock with new components. The single core source and fluctuating time of returning cores creates a need to balance the system by seeding from new components. According to Abbey et al. (2019), companies have used seeding to combat the scarcity of usable cores for remanufacturing operations. According to them, by using seeding a company can increase core return volumes and as a result, start circular manufacturing

operations earlier. Seeding secures a stable availability for reuse parts resulting in a more stable flow of cores when those have become EOU (Abbey et al., 2019). One of the questions with seeding has to do with profitability since new parts are sold with generally lower reuse pricing. Abbey et al. (2019) studied the economical impact of seeding on profitability, and concluded that seeding can have a profit-increasing effect on reuse parts during the product's lifecycle in the diesel engine industry. To add, the case company of this study also saw other benefits in reuse products than mere profit. The fact that EOU cores are collected from the field helps the company to protect their intellectual property.

In an optimal scenario, the reuse part stock should always have parts available for pending customer orders. Customers get their parts and, the circulation of reuse parts remains undisturbed. The approach to seeding should, however, be coordinated since when the company starts to replenish reuse stock with new components, this naturally affects the availability of the new components. Therefore, the company may need to assess their replenishment needs in advance to secure availability for the new component. It was also noted that reuse fuel pumps were more often suffering from missing cores; this was expected to result from the fact that the pumps could be circular manufactured only once before disposal. This naturally limits the total number of pumps in circulation, especially when compared to injection valves, where the number of cycles was found to be three. The reuse fuel pumps would require more frequent transfer of new parts than the reuse injection valves.

7 Conclusion and future research

This chapter concludes this research by providing an overall summary of the essential findings and how these answer the initial research questions and aims. Also, contributions to the existing body of knowledge are discussed. The chapter is closed by acknowledging any limitations and providing suggestions for future research in this field.

This research aimed to identify challenges that contributed to demand and supply imbalance in a CLSC system. Conducted interviews and rigorous analysis provided 14 different challenge categories across the case CLSC. A summary of recognised challenges can be found in Table 2 on page 54. As the second aim, the research was set to narrow down the most critical challenges with PFMEA analysis. As a result, the study indicated that critical challenges in the reverse supply chain process are related to limited internal and external process knowledge and visibility of returning cores. Critical challenges in circular manufacturing order creation and circular manufacturing operations were low core availability for circular manufacturing, a pull-ordering system, outdated inventory management practices, and a missing seeding strategy. As the final aim, the study provided improvement proposals for the case company, which would result in a more balanced demand and supply. The case company should knowingly increase the process knowledge of key stakeholders. Also, changing to push manufacturing strategy for high-volume reuse parts should be considered. Similarly, the current inventory management needs to be reviewed to support the current demand level. Finally, the company should take a more structured approach to seeding reuse stock with new components. The issue with return visibility should also decrease once the company achieves a more stable flow of reuse parts with the methods mentioned above.

This study identified two new challenge areas that impact CLSC demand and supply balance. As new findings, issues arising from poor process knowledge and missing seeding strategy were added to the list of already identified CLSC challenges. The existing studies have discussed CLSC challenges, but no challenges resulting from a missing seeding strategy and poor process knowledge have been identified before. Schenkel et al. (2019)

studied CLSC challenges with four case companies but reported no issues as such. Regarding seeding, Abbey et al. (2019) saw seeding as a supportive tool to ensure a more stable flow of returning cores, however, it was not seen as a vital standard element of a CLSC system. These observations highlight the fact that each CLSC has unique requirements to operate effectively. In the case CLSC, customers as the single core source created the additional requirements for process knowledge and coordinated seeding strategy. Finally, the study ranked observed challenges based on criticality. Since CLSC systems are often ridiculed with issues, this helps managers and future research by narrowing them down to the most critical.

This work studied a single case company's CLSC challenges in a reuse spare part business. Therefore, the challenges found may be different from those in other CLSCs due to different operating environments and products. As well, the qualitative research methodology and PFMEA analysis rely on participants' experiences and knowledge, which may differ among interviewees. Therefore, some level of cautiousness is advised, and the applicability to another CLSC should be verified when applying presented findings to other CLSC systems.

Future research could evaluate CLSC challenges with a larger number of case companies and quantitative research methods. Especially the quantitative methodology could result in interesting findings regarding how observed challenges and criticality vary across industries. Additionally, future research could continue the work in evaluating how to mitigate process knowledge issues in large organisations' CLSC.

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Appendices

Appendix 1. Predetermined interview questions

Participant's background

1. What is your job function?
2. How long have you been working in this function?
3. How long have you been working with reuse parts and what are your tasks?

Reuse parts process and issues

1. In your opinion, why are the reuse parts suffering from demand and supply imbalance?
2. Have you observed problems relating to the flow of materials?
3. Have you observed problems resulting from poor flow of information?
4. Have you observed problems resulting from varying timing, quantity, and quality of returning cores?
5. Have you observed issues resulting from poor supply chain network design?
6. Have you observed issues in the actual circular manufacturing operation?
7. Have you observed other issues in the process?

Existing process controls and Criticality

1. How is the current process controlled to mitigate existing issues?
2. How does the case company manage core returns?
3. Out of the identified issues, which would you say has the most critical impact on availability?
4. In your opinion, how should the current process be developed to secure better demand and supply balance?

Appendix 2. PFMEA – Process evaluation criteria tables

Table 3. Criteria for severity adapted from AIAG, 2019 and Zhu et al., 2021

Process Evaluation Criteria - Severity		
S	**Effect**	**Impact**
10	High	Failure mode could result in an acute health and safety risk and/or system breakdown without prior warning
9		Failure mode could result a significant permanent consequence (system disruption, service interruption) with prior warning
8	Moderately high	Failure mode could result a significant consequence (high customer dissatisfaction, extensive system repairs, much rework, added costs)
7		
6	Moderately low	Failure mode could result a moderate effect; moderate customer dissatisfaction, system problems
5		
4		Failure mode could result a moderately low effect and moderately annoys customers and/or failure mode results some system problems
3	Low	Failure mode could result a minor effect and slightly annoys customers and/or failure mode results minor system problems
2		Slight inconvenience to process, operation, or operator
1	Very low	No discernible effect

Table 4. Criteria for occurrence adapted from AIAG, 2019

Process Evaluation Criteria - Occurrence		
O	**Prediction of Failure Cause Occurring**	**Prevention Controls**
10	Extremely high	No prevention controls
9	Very high	Prevention controls will have little effect in preventing failure cause
8		

7	High	Prevention controls somewhat effective in preventing failure cause
6		
5	Moderate	Prevention controls are effective in preventing failure cause
4		
3	Low	Prevention controls are highly effective in preventing failure cause
2	Very low	
1	Extremely low	Prevention controls are extremely effective in preventing failure cause from occurring

Table 5. Criteria for detection adapted from AIAG, 2019

Process Evaluation Criteria - Detection		
D	**Ability to Detect**	**Opportunity for detection**
10	Very low	The failure mode will not or cannot be detected
9		The failure mode is not easily detected (random checks)
8	Low	Problem detection post processing / Human inspection
7		Detection method (machine-based) that will detect failure mode at source
6	Moderate	Proven detection method that will detect failure mode (Human-based detection)
5		Proven detection method that will detect failure mode (Machine-based detection)
4	High	Detection method that will detect failure mode after processing and prevent further processing
3		Detection method that will detect failure mode at source and prevent further processing
2		Detection method that will detect the cause and prevent the failure mode
1	Very high	Failure mode cannot occur, or it is always detected

Appendix 3. PFMEA – Action priority table

Table 6. Action priority table adapted from AIAG, 2019

Action priority (AP) for PFMEA						
Effect	**S**	**Prediction of Failure Cause Occurring**	**O**	**Ability to Detect**	**D**	**Action Priority (AP)**
Very high	9-10	Very high	8-10	Low - Very low	7-10	H
				Moderate	5-6	H
				High	2-4	H
				Very high	1	H
		High	6-7	Low - Very low	7-10	H
				Moderate	5-6	H
				High	2-4	H
				Very high	1	H
		Moderate	4-5	Low - Very low	7-10	H
				Moderate	5-6	H
				High	2-4	H
				Very high	1	M
		Low	2-3	Low - Very low	7-10	H
				Moderate	5-6	M
				High	2-4	L
				Very high	1	L
		Very low	1	Very high - Very low	1-10	L
High	7-8	Very high	8-10	Low - Very low	7-10	H
				Moderate	5-6	H
				High	2-4	H
				Very high	1	H
		High	6-7	Low - Very low	7-10	H
				Moderate	5-6	H
				High	2-4	H
				Very high	1	M
		Moderate	4-5	Low - Very low	7-10	H
				Moderate	5-6	M
				High	2-4	M
				Very high	1	M
		Low	2-3	Low - Very low	7-10	M
				Moderate	5-6	M
				High	2-4	L
				Very high	1	L
		Very low	1	Very high - Very low	1-10	L
Moderate	4-6	Very high	8-10	Low - Very low	7-10	H
				Moderate	5-6	H
				High	2-4	M
				Very high	1	M

		High	6-7	Low - Very low	7-10	M
				Moderate	5-6	M
				High	2-4	M
				Very high	1	L
		Moderate	4-5	Low - Very low	7-10	M
				Moderate	5-6	L
				High	2-4	L
				Very high	1	L
		Low	2-3	Low - Very low	7-10	L
				Moderate	5-6	L
				High	2-4	L
				Very high	1	L
		Very low	1	Very high - Very low	1-10	L
Low	2-3	Very high	8-10	Low - Very low	7-10	M
				Moderate	5-6	M
				High	2-4	L
				Very high	1	L
		High	6-7	Low - Very low	7-10	L
				Moderate	5-6	L
				High	2-4	L
				Very high	1	L
		Moderate	4-5	Low - Very low	7-10	L
				Moderate	5-6	L
				High	2-4	L
				Very high	1	L
		Low	2-3	Low - Very low	7-10	L
				Moderate	5-6	L
				High	2-4	L
				Very high	1	L
		Very low	1	Very high - Very low	1-10	L
Very low	1	Very low - Very high	1-10	Very high - Very low	1-10	L

Appendix 4. PFMEA – Sales

FAILURE MODE AND EFFECTS ANALYSIS (PROCESS FMEA)									
Date: 24.2.2023									
Case process: Revers supply chain processes / Core return				Case components: Injection valve 1 Injection valve 2 Injection valve 3 Fuel pump 1 Fuel pump 2					
Organisation: Sales organisation									
Present: Thesis author, Product manager and Process expert									
Process Function/ Require-ments	Failure Mode	Effect(s) of Failure	SEV	Causes/ Mechanisms of Failure	Current Process Con-trols Prevention	OCC	Current Process Controls Detection	DET	**AP**
Customer sends back the core after a new re-use part has been installed	The removed core is not sent back	Lowered core availability for circular manufacturing	9	Customer process knowledge (indirectly internal process knowledge)	Reuse part terms and conditions are pro-vided during the sales phase/Reminders	3	Occasionally email from cus-tomer when core is put into deliv-ery	8	**H**
	Customer sends back the core in unacceptable con-dition (cables cut etc.)	Evidently lowered core availa-bility for circular manufactur-ing due to extra cores taken out of the cycle	9	Customer process knowledge (indirectly internal process knowledge)	Customer is provided with return instruc-tions	2	None, there is no visibility how the core is handled at the customer's end	9	**H**
	Customer sends back the core without the ap-pointed transport box	Slowed process due to addi-tional handling = lowered core availability // Additional cost at the logistic centre	2	Customer process knowledge (indirectly internal process knowledge)	Customer is provided with return instruc-tions	2	None, there is no visibility how cores are handled at the customer's end	9	**L**

Receiving returned cores at the warehouse	Received core cannot be identified	Lowered core availability for circular manufacturing due to slowed process Additional time and resources spend to identify the received core	4	No delivery documents included to the return delivery (Customer process knowledge/Indirectly internal process knowledge)	Customer is provided with return instructions	4	None, there is no visibility how the customer handles the return delivery	9	**M**
	Too damaged or EOL cores are put to stock	Cores that should be disposed end up being sent for further processing, therefore disturbing the process flow	4	Core condition is not thoroughly checked at inbound (Core quality control)	Inbound is instructed to perform a rough visual check (Main goal is to identify that the material number matches with the box contents)	7	Detected when the parts are eventually received at the workshop	8	**M**
	Core is received late (>12 weeks)	Lowered core availability for circular manufacturing	5	Single global return point (Reverse logistic network)	Reminders at steady intervals	7	Return order remains open until the core has returned/Robot follow up	5	**M**
				The core was not sent on time (Supply management)	Reuse part terms and conditions are provided during the sales phase/Reminders	6	Emails to request for the status	8	**M**
	The core still not received after 25 weeks OR the case company is not compensated for the missing core	Lowered core availability for circular manufacturing and costs	8	The core was not sent on time. Undisciplined return follow-up. (Supply management/Internal process knowledge)	Return follow up process	7	Return order remains open until the core has returned Less follow up after 25 weeks being late	7	**H**

Appendix 5. PFMEA – Purchasing

FAILURE MODE AND EFFECTS ANALYSIS (PROCESS FMEA)

Date: 22.2.2023

Case process: Reuse part ordering

Organisation: Purchasing organisation

Present: Thesis author, Strategic purchaser, Operative purchaser, and Inventory planner

Case components: Injection valve 1, Injection valve 2, Injection valve 3, Fuel pump 1, Fuel pump 2

Process Function/ Requirements	Failure Mode	Effect(s) of Failure	SEV	Causes/ Mechanisms of Failure	Current Process Controls Prevention	OCC	Current Process Controls Detection	DET	AP
Place circular manufacturing order for reuse parts	Circular manufacturing order for reuse parts is not placed	Promised delivery lead times cannot be kept, the customer must wait for their parts longer = lowered availability	7	Circular manufacturing order cannot be placed due to missing cores (Circular manufacturing order creation)	None, core returns cannot be predicted right now, and purchasing cannot influence the problem	10	Missing cores can be easily detected by the purchaser	1	**H**
	Circular manufacturing order placed for too low quantity	Process costs (transportation, handling, etc.), when order quantity is small	4	No clearly agreed MOQs (Order lot sizing)	MOQ in place for pilot pumps but not for injection valves	5	Purchaser is usually aware if low qty is ordered	2	**L**
	Circular manufacturing order placed for too high quantity / too large qty of cores shipped to the workshop	Too large quantities of injection valve cores cause storage and handling issues at the workshop	5	No defined Max lots (Order lot sizing)	None or only an oral contract to avoid sending too many at once	5	Purchaser is usually aware if too high qty is ordered at once	6	**L**

	Circular manufacturing order not placed even though cores are available	Lowered reuse part availability for the customer	6	Reactive ordering process (Circular manufacturing order creation / Core inventory management)	No process in place	8	Random checks	9	**H**
Reuse part delivery from the workshop within the agreed lead time	Reuse parts are not delivered within the agreed lead time	Customer must wait longer for their parts	5	Sub-components are ordered only after reuse order creation Required sub-components not available (Sub-component inventory management/Circular manufacturing process)	Some sub-components are held in stock	8	Detected from long lead times/planned delivery date is communicated by the supplier or workshop	8	**H**
				Global supply chain challenges (Sub-component inventory management)	Inventory management	7	Global supply chain challenges are easily detected when discussing with suppliers	4	**M**
Securing reuse part availability	Reuse parts are not available	Customer cannot get their parts	8	No parts transferred from new component stock to reuse part stock (Seeding)	No structured process in place	9	Can be detected but not acted upon / On rare occasions, parts are transferred	8	**H**
				Long reuse part lead times (Circular manufacturing process)	Inventory management/process partly out of purchasing team's control if cores are missing	6	Discussions with workshops and suppliers, order monitoring	1	**M**