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Remanufacturing supply chains: multiple case analysis

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Biographic note

João Pedro Rendeiro Filipe de Sousa was born on July 3rd, 2002, in Viana do Castelo, Portugal. He is currently completing a Master's degree in Management at the Faculty of Economics of the University of Porto. His dissertation focuses on remanufacturing, a topic that allows him to collaborate with four companies to address challenges related to sustainability and supply chain processes. This work marks the conclusion of his master's journey. Prior to this, he earned a Bachelor's degree in Management from the University Portucalense Infante D. Henrique, with a GPA of 15.

During his academic journey, João had the opportunity to study and live in different countries, participating in the ERASMUS+ Programme in Warsaw, Poland, at the Faculty of Management of the University of Warsaw, and in Rome, Italy, at the Università degli Studi di Roma Tor Vergata.

This academic path has been a rewarding and defining chapter in his life. Looking ahead, João is eager to take on new challenges in his professional journey with curiosity, ambition, and optimism. Known for his positive attitude and ever-present smile, he believes life is best approached with confidence, lightness, and a genuine enjoyment of the ride and hopes to carry that energy to others and into everything that comes next.

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To my parents, my brother and the rest of my family, thank you for being by my side in every moment of my life and for supporting every decision I've made along the way. Your love and encouragement have been the foundation of everything I have achieved.

Abstract

Remanufacturing is a cornerstone of the Circular Economy, promoting sustainable practices by restoring end-of-life products to like-new condition while reducing waste and resource consumption. Despite its potential, challenges remain in managing uncertainties in product returns and demand rates, as well as, fostering effective collaboration among supply chain partners. This dissertation, developed in the context of the RENÉE Project funded by Horizon Europe, aims to explore how Supply Chains can be designed and coordinated to enable the effective integration of remanufacturing processes and systems, with an emphasis on managing uncertainties and enhancing Supply Chain visibility. Through qualitative analysis of industrial case studies spanning four sectors—electric motors, robotics, bicycles, and refrigerators—this research highlights practical implications for supply chain design, offering actionable strategies to enhance collaboration and achieve sustainable value chains. The findings advance the understanding and application of scalable, economically viable remanufacturing systems by bridging the gap between academic research and industry application.

Keywords: Remanufacturing, Circular Economy, Sustainability, Value Chain, Circular Supply Chain, Industrial Case Studies.

Resumo

A remanufatura é um pilar fundamental da Economia Circular, promovendo práticas sustentáveis ao restaurar produtos em fim de vida para um estado equivalente ao novo, reduzindo simultaneamente o desperdício e o consumo de recursos. Apesar do seu potencial, persistem desafios na gestão das incertezas associadas aos retornos de produtos e às taxas de procura, bem como na promoção de uma colaboração eficaz entre os parceiros da cadeia de abastecimento. Esta dissertação, desenvolvida no âmbito do Projeto RENÉE, financiado pelo programa Horizonte Europa, tem como objetivo explorar de que forma as cadeias de abastecimento podem ser desenhadas e coordenadas para permitir a integração eficaz de processos e sistemas de remanufatura, com ênfase na gestão de incertezas e no reforço da visibilidade da cadeia. Através de uma análise qualitativa de estudos de caso industriais em quatro sectores — motores eléctricos, robótica, bicicletas e frigoríficos — esta investigação destaca implicações práticas para o design da cadeia de abastecimento, oferecendo estratégias acionáveis para melhorar a colaboração e alcançar cadeias de valor sustentáveis. As conclusões contribuem para o avanço do conhecimento e da aplicação de sistemas de remanufatura escaláveis e economicamente viáveis, colmatando a lacuna entre a investigação académica e a aplicação industrial.

Palavras-chave: Remanufatura, Economia Circular, Sustentabilidade, Cadeia de Valor, Cadeia de Abastecimento Circular, Casos de Estudo Industriais.

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List of Abbreviations

CE – Circular Economy

CLSC – Closed-Loop Supply Chain

CSC – Circular Supply Chain

RL – Reverse Logistics

SC – Supply Chain

SCs – Supply Chains

1. Introduction

Remanufacturing is recognized as a key strategy within the Circular Economy, which, in turn, is an essential area of research for sustainable development in modern society (Mairi Kerin & Duc Truong Pham, 2020). Remanufacturing corresponds to the batch production process of specialized repair of damaged or end-of-life products, where companies recycle end-of-life items, restoring their use value through remanufacturing. Remanufactured products can reach the same quality and performance as the original new product (Peng Wan & Zhiyuan Xie, 2024).

According to Xia and Zhang (2019), remanufactured products can reduce environmental impacts by up to 80% compared to traditional manufacturing processes, making it a critical strategy for achieving sustainability goals. Remanufacturing aligns profitability with sustainable development by reducing waste sent to landfills, as well as minimizing the consumption of virgin materials, energy, and labour required for production. (Ijomah, Childe, and McMahon, 2004).

This study was conducted within the framework of the RENÉE Project, a Horizon Europe-funded initiative that aims to advance remanufacturing through AI, robotics, and digital infrastructures. The project seeks to develop scalable and resilient remanufacturing solutions in key industrial sectors, promoting sustainability and circular value chains. While RENÉE addresses multiple aspects, including technology development, workforce upskilling, and digital product passports, this dissertation focuses specifically on the supply chain dimension of remanufacturing.

To guide the research, the following questions are addressed:

1. How should supply chains be designed to support the implementation of remanufacturing operations?
2. Who are the key actors involved in the remanufacturing process across different sectors?
3. What information should be shared among supply chain partners to reduce uncertainties in the remanufacturing process?

The aim of this dissertation is to explore how supply chains can be developed and coordinated in a way that enables the effective integration of remanufacturing processes and systems, with an emphasis on managing uncertainties and enhancing collaboration along the supply chain.

The study uses a qualitative methodology, taking on case studies with four companies representing different industrial sectors: robotics, electric motors, bicycles, and refrigerators. These use cases provide a rich, real-world foundation for exploring the operational, logistical, and strategic challenges of implementing remanufacturing processes in diverse sectors. The study focuses on uncovering insights through qualitative data analysis, including interviews with key stakeholders, an online questionnaire, document reviews, and observational research within these companies' remanufacturing operations.

In order to identify critical success factors and offer practical strategies for supply chain design that facilitate efficient and scalable remanufacturing, this dissertation will integrate qualitative insights from the four use cases with the body of existing academic literature. The goal is to offer useful suggestions for industry stakeholders while also adding to academic discussions about remanufacturing and the circular economy.

The study is structured into seven chapters. Following this introduction, the second chapter provides a literature review covering circular supply chains and remanufacturing to establish the theoretical framework and research gaps. The third chapter explains the methodology, focusing on multiple case studies and supply chain mapping as analytical tools. The fourth chapter presents the results, organized into four case studies, each addressing a distinct sector. Chapter five discusses the findings, connecting them to existing literature and highlighting their implications. The sixth chapter concludes the dissertation, summarizing the main findings, restating the contributions, and suggesting directions for future research. Finally, Chapter seven includes the references.

2. Literature review

2.1. Circular Supply Chains

The circular supply chain concept is gaining popularity as a solution to the challenges of today's competitive business environment by aligning environmental and economic goals (Masi, Day, & Godsell, 2017).

Circular Supply Chains are organized around the objective of restorative and regenerative use, while systems aim to reduce hazardous materials, reuse resources, and eliminate waste at the industrial level and during the “lifespan" of products and services (Tavera Romero, Castro, Khalaf, & Vargas, 2021). Supply chains aim to improve resource efficiency and maximize environmental benefits, CSC's business strategy prioritizes skilful material application over consumption, resulting in exceptional economic, environmental, and social outcomes (Tavera Romero et al., 2021).

Circular systems reduce reliance on virgin raw materials, reducing production uncertainties (Chhimwal, Agrawal, & Kumar, 2021) and promoting efficient and resilient operations (Alonso-Muñoz, González-Sánchez, Siligardi, & García-Muiña, 2021). By maintaining material loops through reuse, remanufacturing, and recycling, firms can safeguard themselves against fluctuations in raw material availability and associated costs, ensuring more stable production flows and minimizing the impact of supply disruptions (Taddei, Sassanelli, Rosa, & Terzi, 2024).

Companies adopting circular supply chain strategies can differentiate themselves in the market, improving brand reputation and customer loyalty (Sánchez-García, Martínez-Falcó, Marco-Lajara, & Millán-Tudela, 2023). By closing material loops and extending product lifecycles, companies lower their carbon footprint and align with regulatory frameworks aimed at promoting circular economy principles (Rasi, Ismail, Shahbaz, & Sundram, 2023).

Companies and governments, however, face challenges in redesigning current linear supply chains into circular supply networks (Rasi et al., 2023). Vermunt, Negro, Verweij, Kuppens, and Hekkert (2019) identify internal and external barriers to circular supply chain implementation within industries. The researchers identified eight major challenges: societal, market, governmental, financial, technological, knowledge and skill, and managerial.

Rasi et al. (2023) explained these primary challenges by categorizing them into specific sub-challenges:

- Governmental Challenges: Lack of vision, misaligned goals, and conflicts between central and local governments. Moreover, the industry does not offer sufficient incentives for "greener" operations, and there is an absence of laws, policies, and environmental restrictions, leading to significant policy challenges.
- Financial Challenges: A lack of governmental support and funding, combined with higher investment costs and high production costs, creates significant financial barriers to the implementation of circular supply chains.
- Technological Challenges: These challenges stem from insufficient knowledge, follow-up, and information sharing, along with a lack of technology transfer or rapid technological advancements.
- Knowledge and Skill Challenges: The lack of awareness, expertise, and competent laborers further hinders progress. Additionally, inadequate training and development initiatives and a limited understanding of smart waste management complicate circular supply chain efforts.
- Management Challenges: Issues include a lack of top management backing, minimal engagement and assistance from middle and lower-level managers, and poor organizational structure for circular supply chains. Furthermore, there is insufficient planning and leadership commitment to adopt effective CSC principles.
- Framework Challenges: Ineffective frameworks and models, as well as the absence of environmental management certifications, hinder implementation efforts.
- Social Challenges: These arise from a lack of passion and engagement with circular supply chains. Consumers often display negative thinking about circular products and demonstrate low interest in environmentally friendly technology.
- Market Challenges: Challenges in this area include the lack of availability of reusable products, non-uniformity of refurbished products, and limited market interest in environmentally friendly technologies.

The concept of the circular economy seeeks to separate economic growth from resource depletion by keeping materials and products in use for as long as possible, at the heart of this model are resource value retention options (R-imperatives), commonly referred to as the "R hierarchy" (Reike, Vermeulen, & Witjes, 2018).

Historically, the R framework evolved from the basic 3Rs—Reduce, Reuse, Recycle—into more sophisticated hierarchies, such as the 10Rs, reflecting an increasing focus on higher-value retention strategies like Refuse, Repair, and Remanufacture (Cramer, 2017). These Rs are not merely theoretical; they serve as a practical heuristic to guide policymakers, businesses, and academia in achieving circular economy goals (Reike et al., 2018).

The concept of Refuse can refer to either the producer or the consumer (Kirchherr, Reike, & Hekkert, 2017). In the context of consumers, researchers emphasize the decision to purchase or use less, which can be applied to any consumption item intended to reduce waste production (Black & Cherrier, 2010). When used in reference to producers, Refuse actually refers to the Concept and Design Life Cycle, in which product designers have the option to reject the use of particular hazardous materials, design production processes to minimize waste, or, more generally, any virgin material (Bilitewski, 2012).

Rethinking is popular in industrial design and artists communities. Utilizing discarded items or parts that have been modified for a different purpose gives the material a completely new life cycle (Reike et al., 2018).

Reduce is associated with producers and their role in the pre-market stages of the Concept and Design Life Cycle, emphasizing the use of less material per unit of production or referring to "dematerialization" as explicit steps in product design (Lieder and Rashid, 2015).

Re-use from the standpoint of the consumer entails purchasing used goods or finding a buyer for a product that was rarely or never used, perhaps with some minor adjustments or cleaning to restore its quality. (Kirchherr, Reike, & Hekkert, 2017). Online consumer-to-consumer sales of used goods, such as those on eBay and their national counterparts, are becoming more and more significant in this context (Worrell & Reuter, 2014).

The purpose of Repair is to increase the product's lifespan (King et al., 2006). It is described as bringing back to working order (Fernández & Kekäle, 2005) and recreating its original function after minor defects (Stahel, 2010).

When a large multi-component product's overall structure is kept intact while numerous components are replaced or repaired, leading to an overall "upgrade" of the product, the term Refurbish appears to be most appropriate (Fernández & Kekäle, 2005). A certain quality should be achieved (Loomba & Nakashima, 2012), and the use of more recent and sophisticated components should bring the product "up to the state-of-the-art" (Stahel 2010).

Remanufacturing takes end-of-life products back to their original, like-new state, with warranties, performance, and quality comparable to those of new products. (Pawlik, Ijomah, Corney, & Powell, 2022).

Repurposing is giving used items or parts a new purpose, giving the material a completely different life cycle (Reike et al., 2018).

Recycling is the process of using costly technological equipment to process and valorise mixed streams of post-consumer products or post-producer waste streams, this includes melting, shredding, and other procedures to capture (nearly) pure materials (Graedel et al., 2011). One obvious distinction with the higher ROs is that recycled materials are also referred to as "secondary" materials (Worrell and Reuter, 2014) because they can be used anywhere and retain none of the original product structure (Graedel et al., 2011).

Recovery is the process of identifying the energy contained in waste and connecting it to either biomass use (Stahel, 2010) or incineration in conjunction with energy production (Sihvonen & Ritola, 2015).

2.2. Remanufacturing

Remanufacturing is defined as the process of restoring end-of-life products to a like-new condition, ensuring they meet or exceed the original performance and warranty standards (Xia & Zhang, 2019). As a key pillar of the circular economy, remanufacturing contributes to resource efficiency, waste reduction, and sustainable production by extending product lifecycles and minimizing raw material consumption (Wan & Xie, 2024). The remanufacturing process follows a structured sequence of steps, including inspection, sorting, disassembly, cleaning, reprocessing, storage, reassembly, and final testing to ensure quality and reliability (Ke, Chen, Gan, Liu, & Ji, 2024).

The key actors in the remanufacturing system include the original consumers, who return the end-of-life products; reverse logistics providers, who facilitate the collection and transportation; manufacturers responsible for remanufacturing and resale; and secondary market customers who purchase the remanufactured products (Shi, Ma, & Yang, 2024). The integration of smart technologies, such as digital twins and real-time tracking, is increasingly improving the efficiency and traceability of remanufacturing processes, further solidifying its role in sustainable industrial practices (Kerin & Pham, 2020).

Remanufacturing allows businesses to increase productivity and profit by preserving a portion of the product's raw materials and added value during manufacturing (Giuntini &

Gaudette, 2003). Additionally, remanufacturing is becoming more and more popular worldwide because of its advantages for the environment (Barquet et al., 2011).

According to Gunasekara, Gamage, and Punchihewa (2020), remanufacturing is more environmentally friendly than traditional manufacturing since it uses a significantly less energy and materials to produce its products. A remanufactured product uses about 20–25% of the energy used in its original form (Lund, 1985). For example, according to Xu, Liu, and Shi (2006), remanufactured engines can save 80% on their environmental impact and 50%, 60%, and 70% on costs, energy, and raw materials, respectively, when compared to new engines.

It allows companies to expand their market coverage by offering remanufactured products at lower prices, appealing to cost-sensitive customers, this dual-market strategy enhances revenue potential and brand equity (Ferrer & Swaminathan, 2010).

The difficulties remanufacturers encounter are very different from those of traditional manufacturing, and they highlight the features that make production, planning, and control tasks in a remanufacturing process more difficult (Guide Jr., 2000).

The main challenges to achieving profitability remain uncertainties in the acquisition of used goods and parts regarding price, quality, quantity, and customer attitude (Wei et al., 2015). Since remanufactured goods are frequently offered as cheaper and/or lower-quality alternatives to original products, maintaining the market balance requires unique production and pricing strategies (Ferrer & Swaminathan, 2010).

The performance of remanufacturing systems and the quality of remanufactured products are significantly impacted by the uncertain quality of used products and the components/parts that are disassembled from the used products (Guide, Kraus, & Srivastava, 1997). The most important stages in the remanufacturing process are cleaning and repair, which call for major technological advancements to be efficient (Sundin & Bras, 2005).

Certain characteristics of the Reverse Supply Chain make it challenging to plan and manage its phases and activities. For example, when a business gathers used goods, its supplier is typically the end user, making it more difficult to obtain the right quantity of goods when they are returned (Barquet, Rozenfeld, & Forcellini, 2011). Another issue is that used products vary in quality, necessitating thorough inspection (Guide Jr., 2000). In addition, it is necessary to disassemble the gathered goods, set up a network for reverse logistics, and address the high variability in processing times (Guide Jr., Jayaraman, & Linton, 2002).

3. Methodology

This study employs a qualitative research approach to explore and analyse remanufacturing processes across the selected companies. With a focus on cooperation, information exchange, and operational dynamics, the study uses qualitative methods to gain important insights into the planning, challenges, and application of remanufacturing practices.

The data collection methods include document analysis, an online questionnaire and semi-structured interviews with key stakeholder. The initial data was gathered using an online questionnaire, which provided a foundational understanding of the companies' remanufacturing processes and guided the following interviews. Interviews were conducted with managers and other stakeholders directly involved in the remanufacturing processes to gain a better understanding of strategic priorities, operational challenges, and best practices.

3.1. Data Collection

Before initiating the questionnaire and interview phases, this research began with an in-depth analysis of internal project documentation made available at the early stages of participation in the ongoing European initiative. This preliminary material provided a comprehensive foundation for understanding the context, scope, and operational setup of the remanufacturing activities under study.

The documents contained valuable technical descriptions of the remanufacturing environments, existing workflows, challenges, and strategic goals identified by each case. They also presented preliminary requirements and expectations, which proved essential for shaping the research design. This early access to structured and detailed information allowed for a more focused approach to subsequent data collection efforts.

Rather than beginning from a blank slate, the study builds upon this baseline of knowledge, which helped inform the development of key themes explored later in the questionnaire and interviews. Consequently, the document analysis phase served as a crucial starting point, ensuring that later methods were both relevant and aligned with real-world operational priorities already defined within the project.

3.1.1 Online questionnaire

The online questionnaire was developed to collect both quantitative and qualitative data from key stakeholders involved in the remanufacturing process, providing valuable insights to better prepare for the subsequent interviews. It aimed to gather insights into product characteristics, supply chain mapping, and supply chain visibility, which are essential for understanding the challenges and opportunities within the remanufacturing ecosystem.

The questionnaire was designed based on the main research themes and included questions aimed at identifying specific components that can be incorporated into the remanufacturing process, understanding the average lifecycle of the products and their use phase, mapping the roles and locations of supply chain actors, analysing current and future reverse logistics scenarios, and evaluating the type, quality, and timeliness of information exchanged among supply chain partners.

It was created using Google Forms due to its accessibility and ease of use. The questionnaire was distributed electronically to a representative from each of the four companies participating in the project, and responses were collected over a two-week period.

By analysing the responses, the research team aimed to gain a preliminary understanding of key themes, which would help refine the interview questions and focus on specific issues during the subsequent interviews. The complete questionnaire, detailing the questions used to guide this phase of data collection, is included in Appendix 1 for reference.

3.1.2 Interviews

To complement the information collected through the online questionnaire and to gain a more understanding of each company's approach to remanufacturing, a series of preliminary interviews was carried out. These aimed to gather detailed insights into operational practices, strategic objectives, and perceived barriers and opportunities within each firm.

The interviews were conducted online using Microsoft Teams and involved representatives from each of the four companies participating in the RENÉE project. The objective was to explore in greater depth the topics introduced in the questionnaire, such as supply chain design, component recovery, and remanufacturing practices. Each company selected the participants internally, based on their availability and knowledge of the remanufacturing process. These conversations provided valuable qualitative insights into the operational and strategic approaches of each company.

3.2. Case Study Companies

3.2.1 Company A

Company A specializes in the production of household appliances, particularly refrigerators. The company operates with a direct sales model, meaning that it has significant control over its technical assistance network and logistics processes. Its current approach to remanufacturing is focused on refurbishment and spare parts recovery, but there are ongoing discussions on expanding remanufacturing efforts, particularly for critical components.

The interview was conducted with two company representatives, one of whom has over 25 years of experience in quality systems, field quality, and supplier management, specializing in outsourced refrigerator manufacturing. The other participant, who has been with the company for five years, is a data analyst in the quality assurance division. The primary interviewee provided in-depth insights into the company's remanufacturing processes, supply chain structure, and component recovery challenges.

3.2.2 Company B

Company B specializes in the production of electric motors for the automotive industry, primarly supplying components to major car manufacturers. As part of the RENÉE project, the company is exploring the viability of integrating remanufacturing into its operations, focusing on assessing which components from used motors can be recovered and reintroduced into the production process. While remanufacturing is not yet an established part of its production model, the company has begun evaluating potential recovery methods and how reverse logistics could be structured to support the process. Since the company's motors have only been on the market for a short time, the remanufacturing process is still in an exploratory phase, with ongoing efforts to assess which components can be recovered and how to establish an efficient disassembly and testing process.

The interview was conducted with an employee who has been with the company for approximately three and a half years. Initially working in the inverter division, the interviewee transitioned to remanufacturing-related projects in early January. His role involves coordinating technical exchanges between different teams, providing mechanical and test data to the company's technology division, and assisting in the development of disassembly and recovery procedures. The interviewee also oversees site visits to manufacturing plants to observe disassembly methods and help define the inspection processes required for remanufacturing. Given his background, the discussion provided insights into the technical and logistical challenges of remanufacturing electric motors, as well as the company's current focus areas in developing the process

3.2.3 Company C

Company C specializes in the production of industrial robots and automation equipment, operating under an order-based manufacturing model. Unlike companies that maintain inventory, Company C produces machines only after securing a sale, making demand forecasting more complex and impacting the ability to plan remanufacturing at scale. The company operates through two primary sales models: in some countries, it sells directly to end customers, handling delivery, installation, and training. In these cases, it retains some control over machine history and technical details. However, in other regions, it works with intermediaries who manage sales and after-sales services, resulting in limited visibility over machine locations, maintenance, and resale transactions. Tracking is further complicated by the fact that many customers independently perform maintenance and later resell their machines, often without informing the company. It is estimated that 80% of machines follow this path, with only a fraction returning to the company for servicing.

The interview was held with two representatives from the technical and strategic teams. One participant had a background in robot design and assembly, with responsibilities over technical support and refurbishment processes. The other worked closely with the after-sales and business development team. Their combined input helped clarify how the company is navigating the technical, financial, and logistical hurdles of developing a remanufacturing strategy in a market where product returns are inconsistent and hard to predict.

3.2.4 Company D

Company D is a retailer specializing in sports equipment, including bicycles, and has a strong presence in both new and second-hand markets. As part of the RENEE project, the company is exploring how circular economy principles can be applied to its product lifecycle, with a particular focus on recovering and reusing bicycle components. While remanufacturing in the traditional sense, where used components are reintroduced into the production line, does not currently fit within its supply chain, the company is working toward developing a structured reuse and refurbishment system for high-value components. Instead of integrating recovered parts into new bicycle production, the approach focuses on using salvaged parts to repair and refurbish existing bikes, ensuring that high-quality used products remain available in the market.

The interview included multiple representatives from Company D, primarily two individuals with long-standing experience in after-sales services, workshop management, and European research projects. One of the interviewees has been with the company since 2004, leading research activities, particularly those related to EU-funded initiatives like RENEE. Another has worked at Company D since 2009, initially as a technician and later managing regional workshops and maintenance supplier relations. Their insights provided a detailed understanding of the company's current approach to refurbishment, supply chain operations, and the logistical challenges of implementing circular economy practices.

3.3. Data analysis

The data collected from the semi-structured interviews were analysed using NVivo 15, a qualitative data analysis software that supports systematic coding, organisation, and comparison of textual data. The analysis followed a primarily deductive approach, guided by the study's research questions and informed by preliminary engagement with the interview material.

Before formal coding began, an initial round of close reading was conducted on all transcripts. This early review helped surface recurring ideas, vocabulary, and potential conceptual categories. Based on this pre-analysis and relevant literature, a coding framework was constructed to structure the analysis. The framework consisted of five main codes — (1) Supply Chain Design, (2) Actors, (3) Information Sharing, (4) Barriers, and (5) Motivations and Benefits — each encompassing a set of targeted subcodes. These categories were designed to capture the multi-layered dynamics of remanufacturing supply chains, stakeholder roles, data flows, constraints, and strategic drivers. A detailed list of subcodes is included in Appendix 2.

The coding process was informed by methodological guidance from Saldaña (2016), particularly regarding distinctions between codes, categories, and themes. While the initial framework was established in advance, it remained flexible and iterative. Codes were refined, added, or merged throughout the analysis to accommodate emergent meanings and ensure analytical coherence.

All transcripts were fully reviewed in NVivo, and relevant data segments were assigned to the most appropriate subcodes. This organisation enabled a structured exploration of thematic patterns both within and across cases. The final stage of analysis involved identifying higher-order themes and relationships between categories, facilitating interpretation in direct alignment with the study's objectives.

4. Results

4.1. Case A

Currently, Company A remanufacturing-related activities focus on refurbishing returned refrigerators and recovering key components for spare parts. The main components targeted for recovery include PCBs (printed circuit boards), fans, motors, heaters, and compressors. These components are considered critical to product functionality, and failures in these parts significantly impact product performance. The PCB is the easiest to recover, as the company has testing and image processing systems in place to evaluate its condition. Other components, such as compressors, require more complex testing and cannot yet be reused at scale. However, the company has plans to expand compressor collection and testing in the future, potentially through a new European project.

The company's approach to remanufacturing is highly selective. Only refrigerators returned within three months of use are considered for refurbishment. If a unit is returned after three months, it is typically scrapped rather than refurbished, as longer product use increases uncertainty regarding remaining lifespan and component reliability. The company is currently studying how to better assess the remaining lifespan of returned products and components to improve decision-making regarding refurbishment versus scrapping.

One of the main reasons products are returned is transportation damage, as Turkey's geographical conditions make long-distance shipping challenging. Many returns involve cosmetic defects, minor functionality issues, or customer-initiated returns under consumer protection laws. In cases where refrigerators have more severe functional failures (e.g., gas leakage), the company does not refurbish them but instead scraps them.

The company has a structured reverse logistics system that ensures returned products are processed through its own service network. Customers do not return products directly; instead, regional technical service centers manage returns and repairs. The company operates nine regional service centers in Turkey, which oversee 30-40 individual service stations each. These regional centers coordinate the flow of returned products and spare parts back to the company's central facility. Company A does not rely on intermediaries or external service providers for refurbishment, meaning it has full control over the return and repair process. The only third-party involvement is in transportation logistics. The projected future supply chain designed to support this remanufacturing strategy is illustrated in Figure 1.

The refurbishment process is highly manual, involving disassembly, cleaning, component testing, and repairs. Given that refrigerators are used in household environments, ensuring hygiene in refurbished products is a critical concern. The company has developed specialized cleaning procedures in collaboration with its R&D department, ensuring that refurbished units meet hygiene and quality standards. However, manual processes limit efficiency, and the company is exploring automation solutions to improve productivity.

Although the company does not currently integrate recovered components into new production lines, it does reuse salvaged parts as spare parts for servicing existing refrigerators. This is not due to legal restrictions but rather a matter of availability, as the volume of recovered parts is not sufficient to meet mass production needs. The company is required by Turkish law to provide spare parts for at least 10 years, which aligns with similar European Union regulations.

From a traceability standpoint, the company has a strong data management system that tracks refrigerators from production to end-of-life. It maintains records of product maintenance history, repairs, and customer interactions, allowing it to analyze product performance over time. This level of visibility is rare compared to other companies in the study, making Company A one of the most advanced in traceability practices. However, despite having extensive product data, the company lacks a model for predicting remaining product lifespan, which it is working to develop within the RENEE project.

One of the biggest challenges for scaling remanufacturing efforts is capacity constraints. The company currently receives around 70,000 returned refrigerators per year, but only 18% are refurbished, with the rest being scrapped. This is largely due to limited processing capacity at return centers. To address this, the company plans to expand its refurbishment capabilities by adding new processing areas and increasing workforce availability during peak seasons (e.g., summer months when return volumes are higher).

Additionally, the company operates its own recycling facility for refrigerators that cannot be refurbished. The recycling process involves shredding and material separation, allowing for the recovery of plastics, metals (steel, aluminum, copper), and refrigerants. While this facility is currently focused on handling internal scrap, the company sees potential for expanding its recycling business in the future.

The primary motivations for engaging in refurbishment and remanufacturing are environmental and financial. The company's corporate strategy places strong emphasis on sustainability, aligning with both national regulations and broader circular economy goals. At the same time, remanufacturing offers cost savings, particularly in spare part availability and reducing new production needs.

Looking ahead, the company is actively investing in improving refurbishment efficiency, studying component lifespan prediction models, and expanding automation in return centers. While remanufacturing is not yet a fully developed part of its business model, it is being explored as a long-term strategic opportunity.

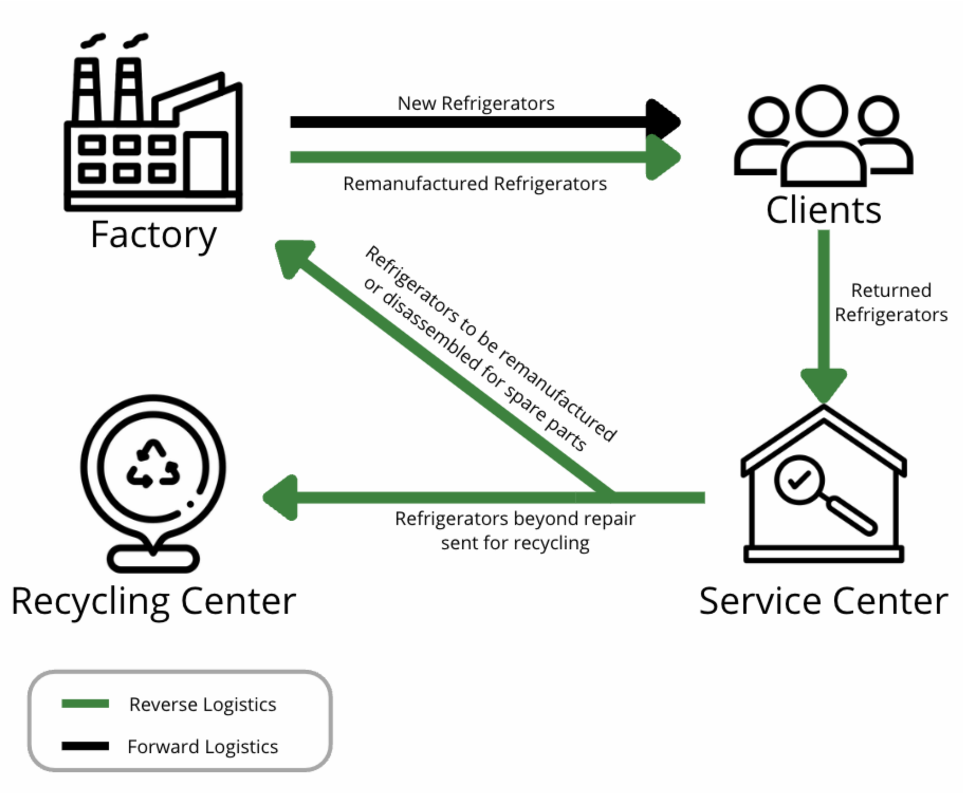

Figure 1 – Predicted future supply chain after implementing remanufacturing – Company A

4.2. Case B

Company B approach to remanufacturing focuses on evaluating the viability of reusing key components, including the housing, stator, and rotor. These parts are critical to the motor's function, but their current design does not facilitate easy disassembly or reuse. For instance, the stator is mounted using a heat-pressing technique that complicates removal, and the rotor contains strong magnets that are difficult to extract without damaging their properties. Unlike traditional mechanical components, electric motors involve complex interactions between electronic and mechanical parts, which makes it challenging to recover certain materials without affecting performance. As a result, the company is currently working on developing efficient methods for component extraction and testing. The long-term goal is to establish a structured process for assessing whether a motor can be remanufactured, which components can be salvaged, and what modifications might be necessary to ensure compatibility with future designs.

One of the main challenges to implementing remanufacturing at Company B is traceability. While the company tracks its motors throughout production and vehicle integration, information gaps emerge once the product reaches the consumer. Repairs performed outside the official network are not systematically recorded, making it difficult to assess the condition of motors upon return. This creates uncertainty in determining which components are suitable for remanufacturing. Despite this, the company has established a comprehensive end-of-line testing system, capturing key performance data such as speed and torque resistance. This data could play a crucial role in evaluating the feasibility of component reuse. However, improving visibility over the product's full lifecycle remains a key challenge.

The company operates within a structured supply chain where its primary client is a major automotive manufacturer that integrates its motors into vehicles. This client is not only the main recipient of the motors but also the key actor in any future remanufacturing process, as the company envisions that product returns will flow back through this client's network. Instead of collecting used motors directly from consumers or independent workshops, Company B expects returned components to first be processed by the automotive manufacturer before being sent for remanufacturing. This centralized return system simplifies reverse logistics by ensuring that all motors originate from a known source, reducing variability in quality and improving traceability. However, this dependence on a single channel also means that the company must work closely with its client to align strategies for remanufacturing. This process is shown in Figure 2.

Beyond the primary client, other key actors in the remanufacturing supply chain include technical assistance and repair centers, suppliers of new components, and logistics providers. Currently, Company B does not receive direct data from repair centers, limiting its ability to track repairs, failures, or product interventions over time. Establishing better data-sharing agreements with these entities would improve the identification of remanufacturable components. Additionally, while some parts of the motor may be reusable, others will require replacement with new components, meaning that coordination with suppliers will remain essential. Logistics providers also play a key role, as motors are manufactured and assembled in different regions, requiring an efficient transport network for both forward and reverse logistics.

Several logistical and operational barriers have been identified in scaling up remanufacturing. First, the unpredictability of returned motors makes supply planning more complex than in traditional manufacturing, where production volumes are carefully forecasted. The company must develop a systematic process to evaluate the quality of returned motors and determine whether components can be recovered or if new parts are required. Additionally, it is still assessing whether remanufacturing should be managed internally or outsourced to third-party remanufacturers, a decision that will significantly impact the supply chain structure.

Despite these challenges, the company views remanufacturing as a strategic necessity rather than an optional initiative. The main obstacles include the lack of design considerations for disassembly, uncertainties about the condition of returned components, and the complexity of setting up an efficient recovery and inspection process. However, the company recognizes that continuing with a linear production model, where products are simply manufactured, used, and discarded, will not be sustainable in the long run.

The expected benefits of remanufacturing include cost reductions, improved resource efficiency, and alignment with environmental regulations. Additionally, there is a commercial opportunity to offer remanufactured motors as a lower-cost alternative to new ones, provided that quality and reliability can be ensured. Although the company is still in the early stages of developing a structured remanufacturing process, it is actively exploring solutions and considering design adaptations to facilitate component reuse in future motor generations.

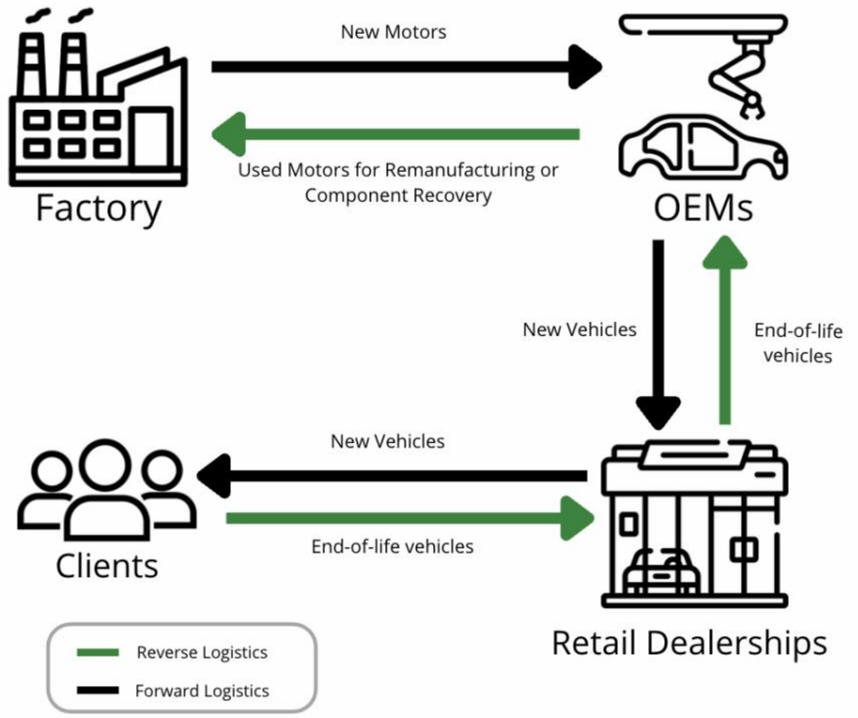

Figure 2 - Predicted future supply chain after implementing remanufacturing – Company B

4.3. Case C

Company C, currently, engages in repair and refurbishment, but at a smaller scale than desired. The focus is primarily on larger, high-value robots, while smaller units are only refurbished under certain conditions, typically when they are in exceptionally good condition or if a customer specifically requests to retain a particular model. The main components being evaluated for reuse include iron and aluminium parts, motors, IO boards, servo drives, and gearboxes. However, the feasibility of reusing parts is strongly linked to the machine's age, as older robots often face technological obsolescence and wear-related limitations.

Despite these existing circular efforts, the company envisions expanding its operations beyond refurbishment to include a full remanufacturing process. This would involve upgrading machines with new functionalities, reassigning serial numbers, and reintroducing them to the market as "as new" products. One major strategic shift the company is considering is moving from a sales model to a rental-based model, which would give it greater control over machine life cycles and facilitate systematic remanufacturing. By leasing rather than selling robots, the company could ensure that products return at predefined intervals for upgrades, repairs, or remanufacturing, rather than being resold by customers without oversight.

Reverse logistics is highly dependent on the sales model. In direct sales markets, used machines can be returned to the OEM factory, following a structured flow from the customer back to the company. However, in intermediary-driven sales markets, there is no formal return system, as the company does not maintain relationships with second-hand buyers. This lack of control over reverse logistics is a major challenge for scaling remanufacturing efforts. Figure 3 shows how the logistics flows work depending on the sales model.

The remanufacturing supply chain involves several key actors. The primary customers play an essential role, particularly in direct sales markets, where they have the option to return machines for refurbishment or remanufacturing. Technical assistance teams handle servicing and repairs, but when machines are sold through intermediaries, third-party service providers are often responsible for maintenance, creating gaps in data collection. Additionally, suppliers contribute by providing complementary components, as not all parts can be reused. The company has identified specific materials, such as steel and aluminium, as particularly valuable for reuse due to their high cost when purchased new.

The biggest challenge in scaling remanufacturing is economic viability. The process is expensive, and although industrial robots are high-value assets, they do not always retain enough residual value to justify extensive remanufacturing investments. The high cost of remanufacturing processes combined with the relatively low resale value of certain robots makes it difficult to establish a profitable model. Furthermore, robots have an average lifespan of 180 months, meaning that they remain in operation for long periods before returning to the company, further limiting remanufacturing volumes.

From a data-sharing perspective, the company has identified key types of information that need to be shared among supply chain actors to facilitate remanufacturing. These include product ID, technical specifications, production and sales dates, warranty activation, and maintenance history. However, given the limited control over machines sold through intermediaries, access to this data remains inconsistent and in need of improvement. While some product history is available, there are still gaps in traceability that hinder effective remanufacturing planning.

Despite these challenges, the company sees clear benefits in remanufacturing, including cost savings, reduced lead times, and improved resource efficiency. By reusing high-cost materials and reducing the 6-8 week production cycle for new robots, remanufacturing could provide a competitive advantage, particularly for customers with urgent needs. However, specific steps for making remanufacturing financially viable have not yet been outlined.

Looking ahead, the company is actively exploring how to integrate remanufacturing into its broader business strategy. The shift to a rental-based model is expected to strengthen its ability to retrieve and remanufacture used robots, but further developments in data-sharing, reverse logistics, and supply chain coordination will be essential to achieving these goals.

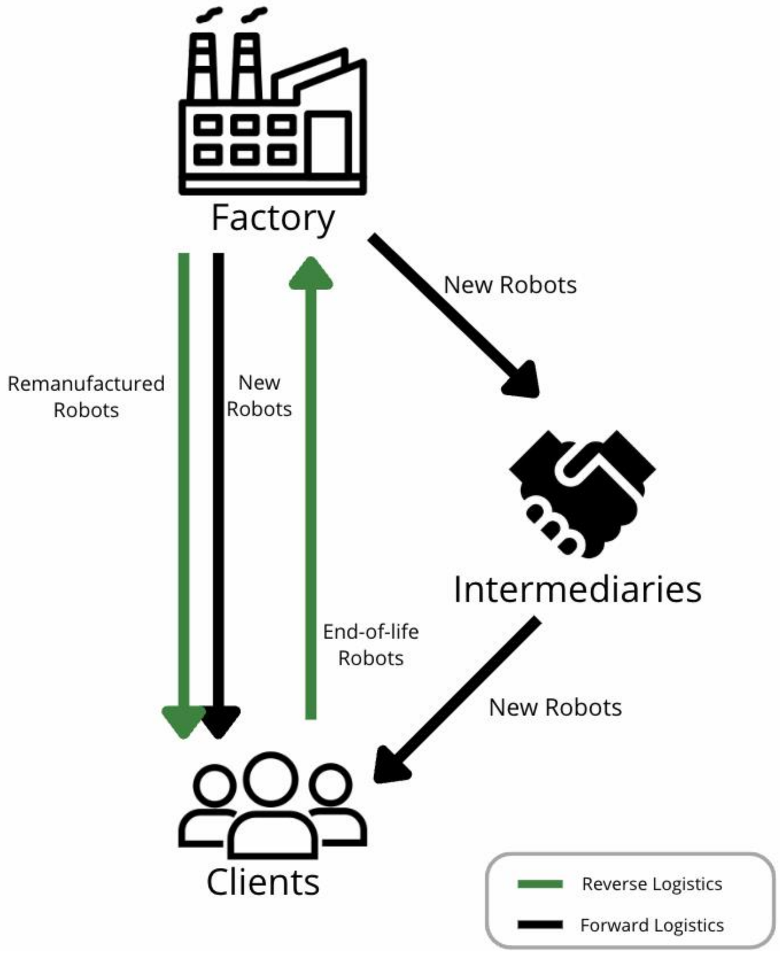

Figure 3 - Predicted future supply chain after implementing remanufacturing – Company C

4.4. Case D

Company D current strategy is focused on recovering components from used bicycles that are returned through their stores. The primary aim is to determine whether parts from damaged or unwanted bikes—particularly frames, forks, and wheels—can be repurposed for repairing or assembling other second-hand bicycles. A major challenge in this process is establishing clear and objective criteria for assessing the condition and value of used components. At present, evaluations are largely subjective, relying on the experience and skill level of workshop staff. The company aims to develop standardized methods that can support employees in making consistent and reliable assessments, reducing the variability in refurbishment decisions.

Unlike traditional remanufacturing models, where components return to centralized production facilities, Company D envisions a localized approach that integrates stores and regional workshops into the circular process. The company operates a dual reverse logistics system, where returned bicycles and components are either processed in-store or sent to centralized workshops for more complex repairs and part recovery. While in-store refurbishment allows direct interaction with customers and quicker turnaround, centralized facilities offer advantages in component stock management and resource allocation across multiple locations. This structure enables the company to redistribute salvaged parts where they are needed most, optimizing the supply of high-value components to different stores. This process is shown in Figure 4.

The supply chain for this model involves several key actors. Customers play a central role as they return used bicycles to the company's stores, which serve as the primary collection points. From there, bicycles and components are either repaired and resold at the same location or sent to centralized workshops for further processing. In contrast to some industries where external service providers handle repairs, Company D currently manages refurbishment internally, with no third-party technical assistance involved. However, the company acknowledges that in the future, external suppliers could potentially be integrated into the process, similar to how they already support new product assembly and quality control.

One of the biggest logistical challenges in expanding the second-hand bicycle market is uncertainty regarding the volume and quality of returned products. Unlike new production, where supply chains operate with predictable manufacturing schedules, circular models rely on the availability of used products, which varies significantly. Currently, each store operates independently, meaning there is no centralized visibility of available second-hand bicycles across different locations. This creates inefficiencies, as high-quality used components in one store might not be accessible to another store that needs them. The company is considering developing a shared database where stores can track available second-hand components and bicycles, allowing for better resource distribution and reducing waste.

From an information-sharing perspective, Company D already has a traceability system that logs details on new bicycles and safety-critical components, primarily for customer safety and recall management. This system is linked to customer loyalty accounts, allowing the company to track maintenance history and interventions—but only for bicycles purchased within its network. The next step in improving traceability is shifting from a customer-centric tracking system to a product-based system, where each bicycle and its components have individual records independent of ownership changes. This would allow for better lifecycle tracking, even when bicycles are resold or transferred between users.

Despite the challenges, the company sees circular models as an essential part of its business strategy, particularly for lower-end market segments. Unlike premium new bicycles, which can be expensive to produce with high-quality materials, refurbished and second-hand bicycles provide an alternative for customers seeking affordable options. The company believes that expanding second-hand offerings can serve as an entry point for new cyclists while also contributing to sustainability goals by reducing demand for raw materials. Additionally, certain bicycle categories, such as children's bikes, represent an especially promising area for refurbishment, as customers frequently replace them due to size rather than wear and tear.

The company identifies three primary barriers to fully implementing circular models at scale. First, the lack of standardized assessment criteria makes it difficult to determine when parts should be reused or discarded. Second, the current IT infrastructure does not support centralized tracking of second-hand products, limiting the ability to redistribute inventory efficiently. Third, while in-store refurbishment works well at a local level, scaling the process requires a more structured reverse logistics system that enables inter-store transfers and centralized repairs.

Despite these hurdles, the company sees strong potential in expanding second-hand and refurbished bicycle sales. The key expected benefits include business growth in the second-hand market, improved sustainability, and a stronger competitive position in circular economy initiatives. Interestingly, unlike some manufacturing companies that pursue remanufacturing for cost reduction, Company D acknowledges that managing new products is currently more efficient than handling second-hand ones. However, it views the circular economy as a long-term strategic opportunity, particularly as regulatory frameworks and consumer attitudes shift toward more sustainable consumption patterns.

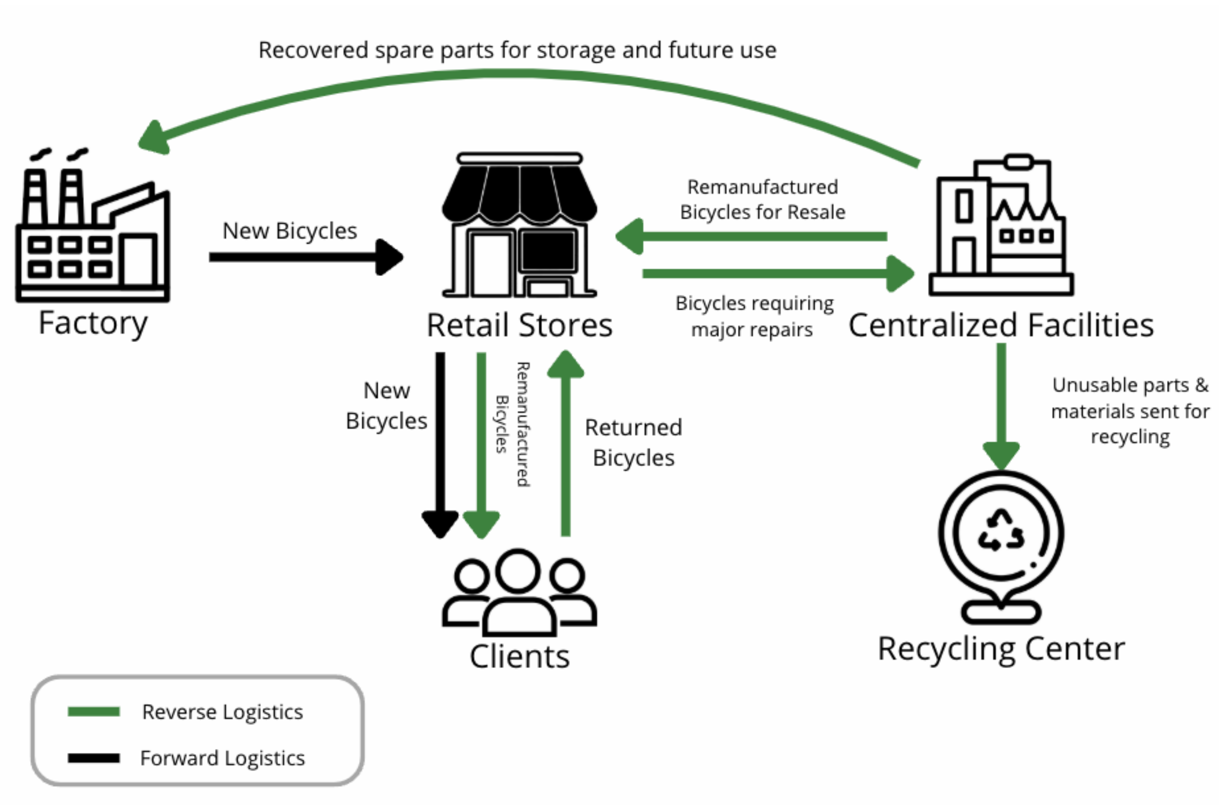

Figure 4 - Predicted future supply chain after implementing remanufacturing – Company D

5. Discussion

This chapter presents a critical discussion of the empirical findings, based on the content analysis conducted in NVivo and structured around the five thematic codes: Supply Chain Design, Actors, Information Sharing, Barriers, and Motivations and Benefits. The discussion compares the four case studies, emphasizing the similarities and differences in how each company approaches remanufacturing. These comparisons are then contrasted with the literature presented in Chapter 2 to consider how real-world practices align with or differ from academic and theoretical frameworks.

Among the companies studied, significant variation exists in how supply chains are structured to enable remanufacturing. Company A shows the highest level of structural maturity. It operates a fully centralized return and refurbishment model managed by a franchised technical service network, with products returning to the headquarters for evaluation and processing. One interviewee explained, “Everything comes back to us. The trucks go directly from the service network to the warehouse.” This high level of centralization facilitates process control, allows consistent evaluation criteria, and supports planned investments in automation. This case supports the work of Rasi et al. (2023), who argue that a centralized supply chain configuration enhances scalability and monitoring in remanufacturing.

Company C, in contrast, has no formal return structure except when products are sold directly. As one participant stated, “We only get the machines back when we sell directly to the client. Otherwise, we lose track completely.” The absence of visibility and the reliance on client initiative illustrate a reactive approach that matches the challenges described by Kerin and Pham (2020) for firms lacking reverse logistics systems. Company D offers a hybrid model, relying on store-based repairs and a few regional hubs. However, as one manager admitted, “There is no tool to tell us the quality and amount of components we have in other stores.” This operational fragmentation leads to inefficiencies and illustrates the difficulty of aligning decentralized execution with a central strategy. Company B does not currently implement a return flow at all, with responsibility fully delegated to a parent OEM. “We don’t collect the products. The OEM does,” a manager stated, “We don’t even know how long they’ve been used.” This reinforces the idea that remanufacturing readiness is deeply intertwined with the firm’s degree of operational autonomy, a point also stressed in

Shi et al. (2024). These differences are summarized in Table 1, which compares the supply chain structures and return flow mechanisms across the four companies.

Table 1 - Cross-case analysis of supply chain design

Companies	A	B	C	D
Return Flow Type	Active	Not implemented	Partial (direct sales)	Active (hybrid)
Centralization Level	Fully centralized	Not applicable	Partially decentralized	Mixed (store + hubs)
Visibility of Returns	High	Very low	Low (except direct sales)	Low
Reverse Logistics Structure	Internal service network	Delegated to OEM	Dependent on sales model	Dual: in-store and regional hubs

The actor dimension further explains the structural differences observed. Company A benefits from internal coordination and clear role assignment across its service providers, internal warehouses, and logistics operators. This vertically integrated configuration supports timely decision-making and reduces transactional frictions. Companies C and B, by contrast, are constrained by their dependency on intermediaries or external OEMs. In Company B, the lack of control over disassembly, logistics, and data gathering is a direct result of relying on Stellantis. This finding aligns with Sundin and Bras (2005), who argue that fragmented responsibility among actors leads to weak coordination and low responsiveness. Company D sits in the middle: although its technicians are part of the internal network, the decentralised structure results in inconsistent procedures and poor information flow between stores. This reinforces Kerin and Pham's (2020) view that actor alignment, not just presence, is key to supporting circular processes.

Notably, only Company A appears to have successfully integrated its actor ecosystem in a way that supports both operational efficiency and strategic control. The other cases, particularly Companies B and C, illustrate that outsourcing or distributing critical remanufacturing tasks without clear information loops introduces gaps in quality, timing, and transparency. Table 2 provides a comparative overview of actor roles and coordination levels across the four companies.

Table 2 - Actor Roles and Coordination in the Remanufacturing Supply Chain

Companies	A	B	C	D
Actor Configuration	Vertically integrated	Dependent on external OEM	Mixed, with intermediaries	Internal technicians, decentralised
Internal Coordination	High	Low	Low	Medium
External Dependencies	Low	High	High	Low–Medium

Information sharing emerged as the most cross-cutting and problematic dimension. Company A stands out as the only firm with full access to intervention records, repair logs, and traceability mechanisms. "We can see the full history of what was repaired and when," one employee explained, pointing to a system where component-level visibility is not only available but actively used. This level of digital integration reflects what Shi et al. (2024) consider essential for reducing uncertainty in reverse operations. Company C, however, reported complete information loss when intermediaries were involved. "We don't know what happened to the machine after it left our factory." Company D provides partial visibility, some stores link repair history to client loyalty cards, but this is not systematically applied across regions. "We can access the client's history, but not always the product's lifecycle." Company B, with no products returned yet, has no systems in place to track usage.

The literature widely emphasises that robust data infrastructure is a prerequisite for effective component evaluation (Vermunt et al., 2019; Ke et al., 2024), and this analysis clearly confirms that. Without access to historical data, firms struggle to assess whether a product is suitable for remanufacturing, increasing the risk of resource waste and inconsistent decisions. While Companies D and B expressed interest in developing traceability systems, these remain conceptual, revealing the implementation gap between intention and capability. These differences in information sharing practices are summarised in Table 3.

Table 3 - Types of Information Shared Among Supply Chain Actors

Information to be shared among actors	Company A	Company B	Company C	Company D
Product ID	X	X	X	X
Product technical characteristics			X	X
Date of production	X			X
Date of the sale to the client (end user)			X	X
History of product interventions	X	X	X	X

The interviews confirm the extensive literature on the practical and strategic barriers that companies face when trying to implement remanufacturing. Company A faces logistical fluctuations, "Summer is a problem. We get too many returns at once and don't have enough people," one employee explained, but has begun investing in robotics to address this. Company C identified disassembly as a major challenge: "Some components are welded or very old. It's just not worth it to remanufacture them." Company D highlighted operational and cost concerns: "Honestly, we're more efficient with new production." Company B, still in early stages, cited both technical and organisational limitations: "We are not involved in disassembly at all. It's not part of our process right now."

These findings confirm what Ferrer and Swaminathan (2010) and Ke et al. (2024) already observed, that barriers to remanufacturing are often systemic and multidimensional. Technical design, capacity constraints, cost-benefit trade-offs, and the absence of structured procedures converge to prevent reman from scaling beyond pilot initiatives. Furthermore, the disconnection between design teams and remanufacturing actors, visible in Company B especially, further highlights the common disconnect between how products are originally designed and the needs of remanufacturing.

The reasons behind engaging with remanufacturing differ considerably across the four companies, ranging from deeply embedded sustainability strategies to emerging commercial interest. For Company A, remanufacturing is both an environmental and operational lever. Its commitment to circularity is not presented as a side project, but rather as a core principle integrated into its long-term efficiency goals. The company clearly links sustainability to measurable improvements in lead times, resource use, and cost optimisation, positioning remanufacturing as a structural advantage rather than a reputational gesture.

Company D, by contrast, frames remanufacturing within the logic of brand value and customer engagement. Its second-life initiatives are tightly connected to the company's public image, and respondents emphasised that "clients like the second-life offer. It adds value to our brand." While its operational systems are not yet optimised for large-scale circularity, the company has found in remanufacturing a way to reinforce its market differentiation. This supports the argument by Sánchez-García et al. (2023) that circular strategies can function as both environmental and marketing assets.

Companies C and B present more forward-looking or aspirational perspectives. Company C, although constrained by technical and financial barriers, appears to be undergoing a shift. As one interviewee put it, "We are rethinking the business model, and there's pressure to prepare for what's coming," indicating that remanufacturing may become more central as part of a broader strategic transition. The firm acknowledges the current inefficiencies but recognises growing pressure, both internal and external, to find viable alternatives to new production. Company B is less advanced but open to transformation. One respondent noted, "We want to be more sustainable, but the reality is that we don't have the tools or the processes yet," reflecting a gap between awareness and capacity. In both cases, remanufacturing is not rejected, but deferred.

These diverse perspectives confirm that motivations for remanufacturing are multi-layered. Environmental responsibility may be a common thread, but its translation into concrete strategy depends on a firm's maturity, structure, and competitive positioning. While some firms see remanufacturing as a route to efficiency or differentiation, others still struggle to connect ambition with feasibility. As Vermunt et al. (2019) suggest, organisational readiness is often the missing link between circular aspirations and implementation. Table 4 summarises the main barriers and motivations identified during the interviews.

Table 4 - Comparison of Remanufacturing Barriers and Motivations

Companies	A	B	C	D
Main Barriers	Seasonal overload, manual processes, limited refurbishment capacity	No disassembly, no logistics control, organisational limits	Technical complexity, disassembly issues, economic viability	Decentralised process, inefficiencies, unclear criteria
Key Motivations	Sustainability as core strategy, efficiency gains	Interest in becoming sustainable, but lacks structure	Strategic repositioning, preparing for future regulation	Brand value, market differentiation, second-life strategy

As demonstrated in this chapter, remanufacturing maturity is not simply a technical milestone, but the result of coherent alignment between actors, information systems, return logistics, and organisational intent. While the literature often assumes that firms motivated by sustainability will naturally advance in circularity, these cases demonstrate that motivation alone is insufficient. Company A is clearly ahead in terms of execution, with Company D making relevant advances in reuse-oriented models. Company C and B remain in earlier stages, constrained respectively by operational fragmentation and structural dependence on external partners. This suggests that for remanufacturing to become an integrated and scalable part of industrial practice, firms must invest in structural redesign, not just pilot initiatives, echoing the foundational conclusions drawn by Vermunt et al. (2019), Shi et al. (2024), and Ke et al. (2024).

6. Conclusion

This study drew upon theories of Circular Economy and Supply Chain Design to examine how supply chains can be structured and coordinated to support the implementation of remanufacturing systems. Focusing on uncertainty management, visibility enhancement, and collaborative alignment, the research aimed to provide insights into the enablers and constraints of remanufacturing adoption across diverse industrial sectors. Using qualitative data from four distinct companies within the RENÉE Project, the analysis revealed how remanufacturing maturity varies considerably depending on organisational structure, actor involvement, and information systems.

The results emphasise that structural integration and strategic alignment are more decisive than motivation alone when it comes to integrating remanufacturing within industrial practice. Firms with dedicated return processes, maintenance data infrastructure, and internal competencies are better positioned to scale remanufacturing operations, whereas others remain limited by fragmentation, external dependencies, or lack of traceability.

6.1. Theoretical Implications

The present study contributes to the existing body of knowledge on remanufacturing and circular supply chains by highlighting that implementation success hinges not only on technological readiness but on the systemic coordination of actors, processes, and information flows. In doing so, it responds to recent calls in the literature to explore how supply chain structures can support operational resilience in remanufacturing contexts.

In addition, this study extends the literature on uncertainty management by demonstrating how remanufacturing introduces unique layers of unpredictability, such as irregular return flows, heterogeneous product conditions, and variable refurbishment feasibility. These factors complicate traditional supply chain planning and therefore require more adaptive and decentralised coordination models.

Another important contribution of the present study lies in its cross-sectorial perspective, offering a comparative view of remanufacturing readiness across four industries. This approach makes visible the integration of supply chain choices in specific industrial realities, challenging assumptions of one-size-fits-all models for circular supply chain design.

The study also contributes to the role of co-design and information sharing in overcoming organisational resistance. By shedding light on the behavioural and relational aspects of circular implementation, the study bridges technical and managerial debates.

Finally, this research offers a methodological contribution by applying qualitative content analysis through NVivo to map cross-case insights, providing a replicable approach for other studies on complex supply chain transformations.

6.2. Managerial implications

The present research adds empirical knowledge to a still-emerging field. The findings have practical implications for several stakeholder groups.

For manufacturing firms, the study may support decision-making on where and how to initiate remanufacturing, by offering a structured understanding of maturity levels, key enablers, and common pitfalls. Managers are encouraged to assess their readiness not only in technical terms, but also in terms of actor alignment and information infrastructure.

For policy-makers and funding bodies, the results corroborate the need to support firms beyond pilot projects, providing incentives for long-term systemic changes. Given the evidence that strategic intent alone does not guarantee operational change, targeted support should prioritise integration capacity and digital infrastructure.
For technology providers and consultants, the findings highlight the importance of tailoring solutions to industry-specific requirements. Flexible and compatible tools may provide a more viable path to widespread adoption, particularly in firms with limited internal R&D resources.

In conclusion, this research reinforces the potential of remanufacturing to act as a lever for sustainable transformation in industrial supply chains, namely in raw materials deficitary regions as Europe. Remanufacturing can secure value added industrial activities, less material and energy demand (and imports), while promoting better jobs and less overall environmental impacts. By uncovering the multi-dimensional nature of readiness and highlighting the structural changes required, the study contributes both theoretically and practically to the advancement of the circular economy. While the path to scalable remanufacturing remains complex, the findings suggest that with appropriate design of logistic supply-chains (namely for reverse direction), collaboration, and support mechanisms, firms can overcome current barriers and unlock the full value of circular production systems.

This offers a positive outlook for future innovation and sustainability in industrial ecosystems.

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Appendixes

Appendix 1 – Online questionnaire

Dear Reneé Project partners.

We request your contribution in responding to this questionnaire. The objective is to understand the current and future remanufacturing process of participating companies and map the supply chain actors involved.

This work is developed within the scope of Task 3.4 of the Reneé project. The information shared here will be used exclusively within the scope of the project and will not be shared beyond the project partners. After the analysis of this enquiry, feedback and further information will be provided by means of interviews to each Reneé's pilot company.

We thank you in advance for your collaboration. If you have any questions, you can contact us via email

Q1: Which company do you represent?

(Mark only one option)

- Company A
- Company B
- Company C
- Company D

Q2: List 5 to 10 components (parts of the company's products) that can be incorporated into the remanufacturing process - which are currently used or could be reused in the context of the Reneé project, when they are at the end of their life.

Q3: What is the average time elapsed between the end of production and the sale of the product to the final consumer (give the answer in months - for example, 2 months). Please consider the main product that is part of the context of the Reneé project.

Q4: What is the average duration of the product use phase (by the end consumer)? (give the answer in months - for example, 36 months). Consider the main product that is part of the Reneé project context.

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Q5: In the current situation, are end-of-life components incorporated into:
(You can choose more than one)

- ☐ Repaired products and/or components
- ☐ Refurbished products and/or components (used products with old specifications)
- ☐ Retrofitted products and/or components (used products with new specifications)
- ☐ Remanufactured products and/or components (“as new” with new serial number)
- ☐ New products and/or components (with new serial number)
- ☐ Other: ______________________

Q6: In the end of the Renée project, will end-of-life components be incorporated into:
(you can choose more than one)

- ☐ Repaired products and/or components
- ☐ Refurbished products and/or components (used products with old specifications)
- ☐ Retrofitted products and/or components (used products with new specifications)
- ☐ Remanufactured products and/or components (“as new” products with new serial number)
- ☐ New products and/or components (with new serial number)
- ☐ Other: ______________________

Q7: Who are the actors involved in the remanufacturing process?
(you can choose more than one)

- ☐ Suppliers
- ☐ Customers
- ☐ Transport companies
- ☐ Technical Assistance
- ☐ Warranty Assistance
- ☐ Waste Treatment Entity
- ☐ Other: ________________________

Q8: Which of the following scenario describes the current reverse logistic for the remanufacturing process?
(You can choose more than one)

- ☐ Consumer → Retailer Facility
- ☐ Consumer → Retailer Facility → [logistic company] → OEM Factory
- ☐ Consumer → [logistic company] → Retailer Facility → [logistic company] → OEM Factory
- ☐ Consumer → Technical Assistance → [logistic company] → OEM Factory
- ☐ Retailer Facility → [logistic company] → OEM Factory [logistics damaged products]
- ☐ Consumer → [logistic company] → OEM Factory
- ☐ Other: ________________________

Q9: Which of the following scenario describes the reverse logistic for the remanufacturing process in the end of the Renée project?
(You can choose more than one)

- ☐ Consumer → Retailer Facility
- ☐ Consumer → Retailer Facility → [logistic company] → OEM Factory
- ☐ Consumer → [logistic company] → Retailer Facility → [logistic company] → OEM Factory
- ☐ Consumer → Technical Assistance → [logistic company] → OEM Factory
- ☐ Retailer Facility → [logistic company] → OEM Factory [logistics damaged products]

- [ ] Consumer → [logistic company] → OEM Factory
- [ ] Other: ______________________

Q10: Where does the used products come from?
[You can choose more than one]

- [ ] In your own country
- [ ] Europe
- [ ] Asia
- [ ] South America
- [ ] North America
- [ ] Africa
- [ ] Other: ______________________

Q11: What information to be shared among supply chain actors is useful for managing the remanufacturing process?

- [ ] Product ID
- [ ] Product technical characteristics
- [ ] Date of production
- [ ] Date of sale to the client (final user) and start of product warranty
- [ ] History of product interventions (e.g., warranty, maintenance, repair, etc)
- [ ] Other: ______________________

Q12: How do the company classify the amount of information shared with the partners?
(Mark only one option)

Table 3: Scale to judge the quantity of information exchanged among partners

Score	Description
1	Unsatisfactory
2	Most of the time we ask for more information from our partner
3	In some case we ask for more information from our partners
4	Satisfactory

- o 1
- o 2

- 3
- 4

Q13: Is relevant information shared or received in a timely manner?

Table 4: Scale to judge the timeliness of the information exchanged among partners

Score	Description
1	Unsatisfactory
2	Information is updated only upon request
3	Information is updated most of the time without request
4	Real time

- 1
- 2
- 3
- 4

Q14: How do the company classify the quality/accuracy/absence of errors of the information shared with partners?

Table 5: Scale to judge the accuracy of the information exchanged among partners

Score	Description
1	Only in few occasions
2	Sometimes
3	Most of the time
4	Always

- 1
- 2
- 3
- 4

Appendix 2 – Coding Framework for Qualitative Data Analysis

1. Supply Chain Design

Subcodes:

- Return_Process_and_Flow
- Disassembly_Practices
- Evaluation_Criteria_for_Reusability
- Centralized_vs_Local_Processing
- Capacity_and_Automation_Needs
- Design_for_Disassembly_or_Service

2. Actors

Subcodes:

- Technical_Service_Providers
- Logistics_and_Warehousing_Partners
- Suppliers_for_Reman_Parts
- Clients_as_Return_Sources
- OEM_Customer_Interfaces

3. Information_Sharing

Subcodes:

- Traceability_and_Product_ID
- Intervention_and_Repair_History
- Data_Availability_Timing
- Missing_Data_in_Indirect_Sales
- Plans_for_Digital_Solutions

4. Barriers

Subcodes:

- Low_Volume_of_Returns
- Difficult_Disassembly
- Inconsistent_Evaluation
- High_Cost_vs_Value_of_Reman

- Data_and_IT_Limitations

5. Motivations_and_Benefits

Subcodes:

- Environmental_Impact_Reduction
- Faster_Lead_Times
- Market_Positioning_and_Second_Life_Strategies
- Strategic_Learning_for_New_Designs
- Cost_Efficiency_Objectives