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A COMPARATIVE ANALYSIS OF ENVIRONMENTAL AND ECONOMIC IMPACTS OF NEW AND REMANUFACTURED INDUSTRIAL EQUIPMENT

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ABSTRACT

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Manufacturing and disposal of industrial equipment contribute to considerable environmental degradation due to high energy consumption, resource depletion, and emissions. The growing pressure to reduce the environmental footprint, and increasingly strict environmental legislation, make remanufacturing a good alternative for industries. Remanufacturing extends product lifespan, reducing the demand for raw material, and making it a more resource-efficient alternative than conventional manufacturing processes.

This study compared the environmental and economic impacts of new and remanufactured Stainless Steel storage tanks. The research used a cradle-to-gate LCA to assess the environmental impacts, including energy, resource use, emissions, and water consumption. Economic analysis was done to compare the cost of new and remanufactured tanks, while a questionnaire-based survey was carried out to explore market perceptions of remanufactured equipment across industries. The results from LCA demonstrated that the remanufactured tank accounted for 95% lower climate change emissions compared to the new one, with the new tank emitting 261 000 kg CO_2 eq and the remanufactured tank emitting only 13 200 kg CO_2 eq. Energy consumption for the remanufactured tank was 94% lower, resource use showed a 97% reduction, and water consumption was reduced by 99% compared to the new tank. Similarly, economic analysis showed that remanufacturing saves 32% in costs compared to manufacturing a new tank. The results of the questionnaires underlined mixed perspectives from the market, with various participants concerned about its performance and reliability.

The findings indicate that remanufacturing can be an efficient way to improve industrial sustainability by substantially reducing emissions, energy, and resource usage. Remanufacturing can assist industries to meet environmental legislation without compromising economic performance. This makes remanufacturing an important strategy for industries, particularly relevant in Europe, where compliance with environmental legislation is gradually becoming compulsory across industries. If remanufacturing increases, it could be of more help in reducing the global environmental burden of heavy industries.

Keywords: Circular Economy, Industrial Equipment, LCA, Manufacturing, Remanufacturing, Sustainability

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PREFACE

My passion for having a positive impact on society has long driven me to figure out my profession, since childhood. The journey of pursuing this dream started long ago, but the feeling of moving forward began after my bachelor's degree in environmental engineering. In a world where sustainability is becoming an absolute necessity, this thesis is a small contribution toward promoting sustainable industrial practices.

I am deeply grateful to Rejlers Finland and the incredible people there who contributed their time and expertise, helping me make this thesis possible. I would like to give my special thanks to Vanessa for giving me this opportunity and to my manager, Pauliina, for her support not only during this thesis but throughout my master's studies. I would also like to thank my supervisors, Hannele and Chunyan, for their guidance and support in steering this work in the right direction throughout the process.

The closure of this chapter would not have been possible without the foundation of support I received from my family. Thank you, Farhan, for reminding Mommy to take deep breaths during overwhelming times; and thank you, Yusuf, for reassuring Mommy that it is OK during tough moments. And as they say, last but not least, my heartfelt thanks also go to my amazing husband, Fuad. Your support and understanding kept me motivated to carry on and allowed me to balance my responsibilities.

Looking ahead to a future where sustainable practices are the norm, as Robert T. Lund said, *"Remanufacturing was 'green' before green was chic."*

Tampere, 9th November 2024

Naheed Amiri-Moghal

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LIST OF SYMBOLS AND ABBREVIATIONS

Cr	Chromium
CE	Circular Economy
CH_4	Methane
COD	Chemical Oxygen Demand
CO_2	Carbon Dioxide
EoL	End of Life
eq	equivalent
GHG	Greenhouse Gas
GWP	Global Warming Potential
Fe	Iron
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoule
Ni	Nickel
NH_4	Ammonium
OEM	Original Equipment Manufacturer
SS	Stainless Steel

1. INTRODUCTION

Greenhouse Gas (GHG) emissions in the manufacturing industry are predicted to increase by 17% from 2024 to 2050 if current energy use continues unchanged (EIA, 2023). In recent years, cost-effectiveness and sustainability have become key concerns in industrial processes (Gholami et al., 2021). Given these imperatives, how can industries reduce emissions without sacrificing economic growth?

Consumers today, value environmental impacts just as much as product functionality and price (Gholami et al., 2021). Industries are now prioritizing sustainability alongside conventional performance indicators due to changing customer preferences (Hojnik et al., 2019). Strict regulations and competitive pressures are driving businesses to find innovative ways to balance cost-efficiency and sustainability (Bittar, 2018; Karakaya et al., 2016). This combined push from industry and legislation has accelerated a shift toward more cost-effective and eco-friendly manufacturing processes. Industrial equipment is essential to many industries, playing a key role in both the global economy and resource consumption. Manufacturing and maintenance of industrial equipment result in substantial global carbon emissions and materials use (Lv et al., 2022). Heavy industries, especially steel production, are among the largest contributors to global emissions (World Steel Association, 2021). At the production stage, high energy use results in emissions, with 1.85 tons of Carbon Dioxide (CO_2) emitted for every ton of steel produced.

Remanufacturing has gained recognition as an environmentally friendly alternative to new manufacturing, which originated in the 20th century (Ling & He, 2020; Lund & Hauser, 2010). Beyond its potential for reducing costs and environmental impact, it is essential to examine how well the remanufactured products stand up to new equipment in terms of performance and durability (Hamzaoui-Essoussi & Linton, 2014). This comparison will focus on factors like carbon emissions, energy efficiency, material consumption, and economic impacts. By diving into these areas, the research hopes to shed light on how remanufacturing might fit into sustainable industry practices in a more meaningful way.

This thesis is conducted in collaboration with Rejlers Finland, a consultancy company that supports sustainable industrial practices. The research aims to use case studies and Life Cycle Assessment (LCA) to explore the environmental impacts at various stages of

the remanufacturing process, from core acquisition to the final product testing. It also addresses operational challenges, such as technical and logistical hurdles, which may complicate remanufacturing efforts (Andrew-Munot & Ibrahim, 2013; Mohamed Nasir et al., 2021). Additionally, the research provides insights into how market perceptions shape the adoption of remanufactured products across industries.

While some studies have investigated specific elements of remanufacturing and sustainability in industrial equipment, comprehensive comparative analyses of both the environmental and economic impacts between remanufactured and new equipment remain limited. This gap is especially evident in the context of Stainless Steel (SS) storage tanks, where combined environmental and economic impact evaluations are underexplored. While many studies have compared new manufacturing with remanufacturing, this thesis provides a more holistic evaluation of environmental, economic, and market assessment within the same framework. It highlights the often-overlooked aspects of energy consumption during remanufacturing, especially for industrial equipment like SS tanks, offering insights into potential energy savings. Additionally, the research covers critical cost components such as compliance and transportation, which are essential for understanding the full economic implications of remanufacturing. This research aims to support industries in adopting sustainable practices within the European context while addressing gaps in the academic literature by providing detailed data on the environmental and economic impacts of remanufacturing.

To achieve these objectives, the study addresses the following research questions:

1. How does the environmental impact of new and remanufactured SS chemical storage tanks differ, investigated through LCA?

2. What are the challenges and opportunities related to remanufacturing industrial equipment, and how does remanufacturing affect the sustainability practices of industries?

3. Beyond the environmental benefits, what are the economic implications of adopting remanufacturing practices in the industrial sector?

2. ENVIRONMENTAL EVALUATION OF STAINLESS STEEL PRODUCTION

2.1 Environmental Impacts of Stainless Steel Production

SS is an iron-based alloy significant due to its corrosion resistance because of its content of chromium (Cr). This metal forms a passive oxide layer which protects it from degradation of the underlying material (Bhadeshia & Honeycombe, 2017). SSs can be classified according to the microstructural features in several types: Austenitic SS, Ferritic SS, Martensitic SS, and Duplex SS. The austenitic type of SS is well known for its anti-corrosion and mechanical stability with good resistance to extreme temperatures and is widely used in making storage tanks (Jha & Arumugham, 2001; Qiu et al., 2021).

One ton of SS production emits between 1.95 to 6.8 tons of CO_2 (Worldstainless, 2024). Over the past two decades, approximately 800 million metric tons of SS have been produced worldwide. The Electric Arc Furnace (EAF) is used in SS production by melting scrap metal with electrical energy, supported by chemical reactions, and heat from oxy-fuel burners (Hernández et al., 2022). The process has three stages: the boredown period, where electrodes are inserted into the scrap, followed by the melting stage, and finally the refining stage, where the metal composition is adjusted. The electrical energy from the arc powers the melting and heating process for around 90% of the batch's lifespan. The melting stage is the most energy-intensive, requiring significant electricity, with an energy efficiency of 60% to 80%. Producing SS has a considerable environmental impact because it demands a large amount of energy and releases GHG (Norgate et al., 2007). It requires a significant amount of energy input since it combines extracted and refined Iron (Fe), Cr, and Nickel (Ni).

The study by Norgate et al. (2007) showed that producing 1 kg of stainless steel requires approximately 75 MJ of energy, using processes like electric furnaces and Argon Oxygen Decarburisation. The study by Johnson et al. (2008) examined the impact of SS production on energy consumption and related CO_2 emissions. Producing one metric ton of austenitic SS using virgin raw materials (with estimated metal concentrations of 74% Fe, 18% Cr, and 8% Ni) requires around 79 GJ of energy. The large amount of energy use is due to the intensive processes involved in the extraction and processing of raw materials. Eccentric Bottom Tapping (EBT) which is a type of EAF, consumes the most energy in SS production, especially during the melting process when molten pig iron and

liquid ferrochrome are utilized (Singhal & Patra, 2013). The energy required for the EBT furnace, using a combination of hot metal and Direct Reduced Iron which is iron ore refined without melting, is estimated at around 16,621 kWh.

This production route is also linked to high emissions of CO_2 (Johnson et al. 2008). In producing one metric ton of SS from virgin raw materials, approximately 5.3 metric tons of CO_2 are emitted. These are emissions related to the burning of fossil fuels for the extraction, transportation, and processing of raw materials like Fe, Cr, and Ni. This makes a strong case for monitoring and further improvement in environmental performance when it comes to steel production to identify its environmental impact. Production of SS also generates an enormous quantity of CO_2, approximately 6.8 kg CO_2 per kg of produced steel (Norgate et al., 2007). Much of this emission is due to the energy used in the production and use of raw materials heavy with carbon. Industrial processes for extracting and processing pig iron (94% Fe), chromite ore (27.0% Cr, 17.4% Fe); laterite ore (2.4% Ni, 13.4% Fe) are very energy-intensive and result in the release of vast volumes of mainly CO_2 through the combustion of fossil fuels.

A large amount of overall GHG can be traced back to raw material transportation to sites for manufacturing, and from product distribution (Johnson et al. 2008). This is mainly due to fossil fuel combustion for freight transport, which forms part of the supply chain associated with primary SS production. A significant share of the total emissions comes from transporting materials over long distances from mines to processing plants. This is because transport is primarily done by diesel-powered vehicles that are relatively inefficient and highly polluting compared with other transport options available today. Bulk mineral shipment involves high emissions, especially for iron ore and coal (McLellan, 2011). For example, iron ore transport represents approximately 172,000 kt of CO_2 eq emissions annually, equal to some 14% of the total direct emissions from the steel industry. Norgate et al. (2007) further elaborate on this point, indicating that the transport stage not only uses a great deal of energy but also generates large volumes of CO_2 gas, which contributes to an increase in the carbon footprint from production.

Waste from raw material extraction and processing in stainless steel production leads to significant environmental challenges (Zhu et al., 2023). Vast amounts of slag and other form of solid waste are generated, which need to be managed with great caution so that it does not contaminate the environment (Norgate et al., 2007). These materials can lead to severe soil and water pollution when this is not treated correctly due to the leaching of toxic materials (Zhu et al., 2023). Johnson et al. (2008) added their input to this topic, discussing the necessity of introducing workable waste management practices. Proper

recycling and reuse strategies could considerably reduce the environmental impact caused by wastes resulting from the production of SS.

2.2 Significance of Environmental Impact Evaluations

Environmental assessment is the systematic process of evaluating the potential impacts of an industrial process and a product (Kareen et al., 2009). It is important to understand and mitigate the adverse effects on the environment to achieve sustainable industrial practices. One of the main methodologies used to evaluate the environmental assessment of a product is LCA. It evaluates a product's environmental impact from raw material extraction to product disposal (Khasreen et al., 2009; Suer et al., 2022). These stages show how industrial processes contribute to environmental degradation, allowing industries to develop strategies to reduce their footprint. These steps are crucial for reducing greenhouse gas emissions, conserving resources, and achieving long-term sustainability (Suer et al., 2022). Environmental evaluation also helps to comply with environmental legislation and improvement of environmental performance at large scales of industries.

Environmental impact assessment for industrial equipment is a crucial factor in sustainable development (Casazza & Barone, 2023). SS is applied across many sectors and features prolonged service life due to its high mechanical properties, and corrosion resistance (Rossi, 2014). This reduces resource consumption over its lifespan by decreasing the frequency of replacements. However, the production process consumes a large amount of energy and emits significant CO_2 emissions, emphasizing the need for detailed environmental assessments. An environmental impact assessment helps evaluate and improve environmental performance by identifying and managing impacts at each stage of the product life (Suer et al., 2022). In addition, the LCA helps identify critical high-impact points in the life cycle such as raw material extraction and production, enabling producers to establish strategies to reduce energy usage and emissions during these stages. All this points out the fact that newer, more efficient technologies and sustainable practices can result in an overall environmental footprint reduction (Casazza & Barone, 2023).

Furthermore, industries must comply with environmental regulations and standards, such as the ISO 14000 series, which outlines proactive systems for managing environmental performance (Santos et al. 2011). For instance, ISO 14001 helps and guides an organization to set environmental objectives and check progress toward the implementation of better performance (ISO 14001, 2015). Such standards would not only

facilitate the needs of regulations but would also provide businesses with a competitive advantage. The standards can be implemented for cost-saving, efficient resource use, and enhancing corporate reputation.

2.3 Applying LCA in Industrial Analysis

LCA is a well-known method for evaluating a product's environmental effects from its creation to disposal (Guinée, 2001). LCA offers a holistic methodology for investigating product-related environmental effects, making it an efficient tool for comparing the environmental footprints of new and remanufactured equipment (ISO 14040, 2006). LCA identifies opportunities for environmental performance improvement and offers meaningful information for decision-making supporting sustainable manufacturing by measuring the inputs and outputs using lifecycle assessment (Hauschild et al., 2018).

The ISO 14040 series outlines LCA in four major phases (Figure 1) (ISO 14040, 2006). It involves an initial step of goal and scope definition to establish the purpose, intended product of the LCA, and system boundary, which will define what will be studied (ISO 14040, 2006). This contains details like functional units; this will specify what is under assessment and, therefore a reasonable core basis for comparison (ISO 14044, 2006). The second phase of the process is the Life Cycle Inventory (LCI), which is the data collection phase (ISO 14040, 2006). In this stage, data is collected to quantify the inputs and outputs linked to the product system. In this stage, all data on the major energy and material inputs, as well as the environmental impact throughout the product's life cycle, from extraction to disposal, are collected. Life Cycle Impact Assessment (LCIA), as the third phase, reads data from the inventory for assessment of the magnitude and importance of potential environmental impacts (ISO 14044, 2006).

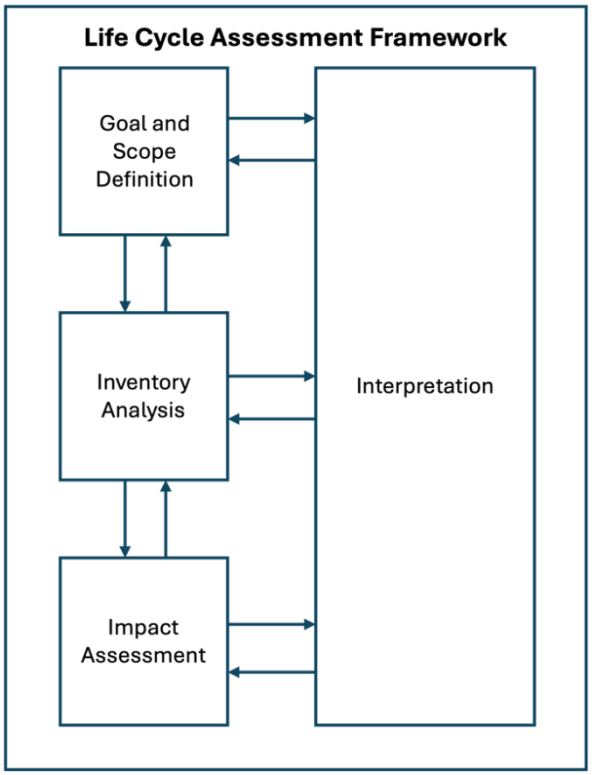

Figure 1 *LCA phases (Adapted from ISO 14040, 2006)*

This phase includes the selection of impact categories, allocation of the given inventory data among these categories, and calculations of category indicators. The last step, Interpretation, interprets the results to draw conclusions and give recommendations for the LCI and LCIA (ISO 14040, 2006). This stage is critical in ensuring that the LCA is clearly understood and used in an accountable way for decision-making processes as per ISO 14040:2006. All the phases are hierarchical to one another or lead to an overall environmentally informed decision.

2.4 Environmental Footprint Analysis in Industrial Manufacturing

The term "footprint" in its environmental context, specifically "ecological footprint," was introduced in the 1990s by Rees (1992). Environmental footprints measure resource use or emissions, or a combination of both (Vanham et al., 2019). In environmental studies, a footprint measures the impact of human activities concerning earth's resources, which initially started as an idea of land use and has been extended today to include different environmental aspects (Matuštík & Kočí, 2021). Environmental footprints measure how our actions impact the environment, such as through the use of water, energy, and materials, and the pollution generated by different activities of production and consumption (Vanham et al., 2019). It considers the overall impact of the industrial

process, including not only carbon emission but also resource depletion, water consumption, and material waste. Besides carbon emissions, critical factors include energy use in material extraction and the use of water in cooling systems. Measuring these impacts allows a comprehensive understanding of the impacts of industrial manufacturing on the environment.

A carbon footprint measures the amount of CO_2 and other GHGs that result from activities, either directly or indirectly, over the life cycles of a product (Wiedmann & Minx, 2008; Vanham et al., 2019). Carbon emissions, along with other GHGs like methane and Nitrous Oxide (N_2O), are part of the environmental footprint. The environmental footprint also includes other factors such as resource depletion and water consumption that are equally vital in determining the impact of the industrial activity. Understanding and monitoring climate-related activities are crucial for identifying how specific actions contribute to climate change (Pandey et al., 2011; Matuštík & Kočí, 2021). This understanding enables more targeted efforts to reduce emissions and mitigate the effects of climate change. Emission reduction slows down the increase in global temperatures, reduces extreme weather conditions, and maintains biodiversity and ecosystems (UNEP, 2015). The increasing emphasis on sustainable practices arises from the increasing calls upon action towards achieving goals by governments, businesses, and individuals.

There are many techniques and tools for measuring emissions (Guinée et al., 2011). The most effective tool for calculating environmental impacts is the LCA method because it considers all the products in the value chain of production to disposal. The input-output analysis assesses broader economic activities and interdependence and can account for the indirect emissions of a product or service. Emission factors assist in translating activities, such as fuel use or electricity consumption, into emissions per activity unit, which helps to understand the level of impact industrial processes have on the environment (Pandey et al., 2011). They allow industries to estimate the emissions that result from various scales of production. These factors are essential in converting activity data to estimates of emissions of GHG to ensure that business and regulatory bodies are informed of their environmental impact accurately (Zhang et al., 2023). Industries, especially those that use vast amounts of energy, like the steel-making industry, can use these factors to understand better what portion of emissions they contribute to climate change and help in the formulation of mitigation measures.

LCA quantifies the total emissions resulting from all stages of the life cycle of both new and remanufactured products (Guinée et al., 2011; Zhang et al., 2023). This approach is

significant for understanding the environmental advantages or disadvantages of choosing remanufactured products over new ones. Results derived from such analysis may also be able to find out some of the roots of associated emission reduction opportunities, which might prove helpful in prioritizing efforts intended for environmental performance improvement in some of the critical areas within the product lifecycle (Pandey et al., 2011).

It was established in Chapter 2 that several critical environmental impacts occur throughout the life cycle of SS and that both resource use and carbon emissions are high. It highlighted the need for sustainable practices where LCA analysis provides essential insights to understand this environmental burden related to production processes. These assessments underline the pressing need for solutions like remanufacturing to offset these impacts. The next chapter will explore remanufacturing concerning Circular Economy (CE) principles that extend product lifecycles and make them more sustainable. This approach is expected to help in reaching the environmental and economic targets through reduced new material demands, reduced energy use, and reduced emissions. More detailed research into remanufacturing processes, together with advantages and obstacles that challenge them, will further outline ways in which this method can effectively transform industry practices.

3. INDUSTRIAL REMANUFACTURING PRACTICES

3.1 Definition and Process of Remanufacturing

Remanufacturing plays a crucial role in CE (Kurilova-Palisaitiene et al., 2020). It is a sophisticated process that transforms used products, referred to as cores, into like-new condition, sometimes even exceeding the original specifications (Hamzaoui-Essoussi & Linton, 2014). Remanufacturing is often confused with similar processes such as repairing, refurbishing, and reconditioning (Ijomah et al., 2007). Repaired, refurbished, and reconditioned products are similar to remanufactured ones: these terms can generally be considered synonymous. Though these terms are somewhat similar, the functionality and performance of each are quite different (Andrew-Munot et al., 2015). The repair only rectifies specific faults in a product; a warranty is only given on the component replaced. Refurbish means cleaning, testing, repackaging replacing non-working parts to get a product working again. A limited warranty accompanies typically such products. Reconditioning entails good cleaning, testing, probable repair, and repackaging for resale. The warranty covers all major wearing parts but is not correspondent of a new product's warranty.

Article 5 of the EU Regulation 2024/1781, under the EU's CE Action Plan, states requirements for eco-design and for products to have the potential for remanufacturing (Regulation EU, 2024). It also emphasizes the need to reduce environmental impacts, such as the environmental footprint. Remanufacturing also aligns with the EU legislation established in 2020 on energy reduction, and CE principles, as well as Original Equipment Manufacturer (OEM) responsibility for taking care of their products long after sale (BS EN 45553:2020, 2020; Pouikli, 2020). The regulations, such as Extended Producer Responsibility (EPR), require producers to take life-cycle responsibility for their products (Pouikli, 2020). Remanufacturing equipment also contributes to achieving SDG goals such as SDG 8 and 12 (Schröder & Barrie, 2024). Thus, remanufacturing helps compliance with environmental and sustainability regulations.

In the remanufacturing sector, businesses are generally divided into two main categories: OEMs and non-OEMs (Parker et al., 2015). An OEM is a company manufacturing products and selling them to be able to facilitate its products in their lifecycle with after-sale services and replacement parts under its brand (Parker et al., 2015; Vogt Duberg et

al., 2020). This closed-loop approach ensures the quality and efficiency of the remanufactured product. Such a business model not only contributes to resource sustainability through extended product life cycles but also reinforces brand trust and loyalty with the assurance of quality and reliability in the remanufactured product. This places OEMs at a unique advantage within the remanufacturing industry since they can produce products and have the facilities to collect them towards the End of Life (EoL) for remanufacturing (Parker et al., 2015). Integrated control of manufacturing and remanufacturing processes can be ensured given high standards in quality and efficiency. On the other hand, since non-OEMs are not provided with the original manufacturing details, they might be unable to reproduce similar quality and efficiency as OEM-remanufactured products. This difference brings out the strategic advantage available to OEMs in staying sustainable and providing better service in the remanufacturing industry. The remanufacturing process takes place in a closed-loop cycle of nine successive stages (Figure 2) for the extension of the product life cycles with minimum effects on the environment (Baballe et al., 2023).

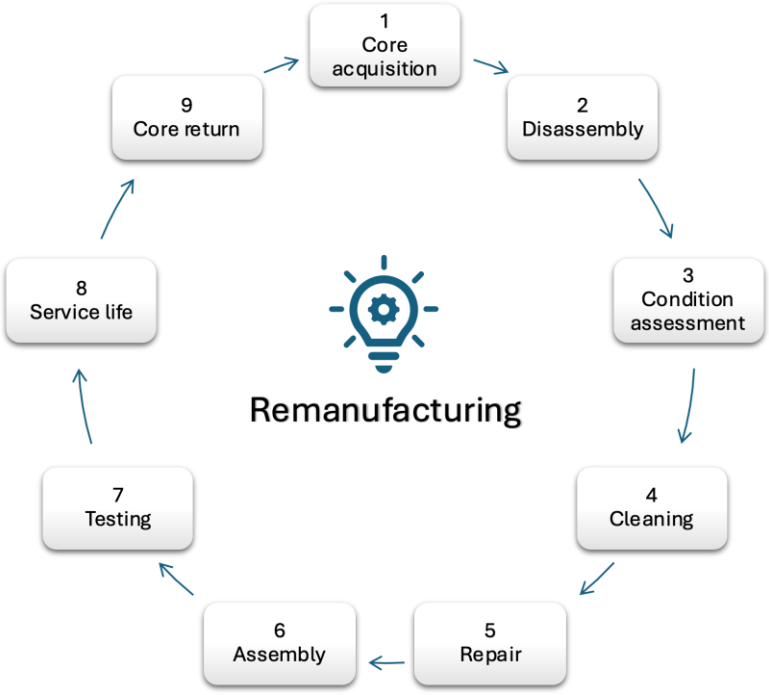

Figure 2 *Remanufacturing process (Adapted from Baballe et al., 2023)*

First, used products eligible for the remanufacturing process are gathered and acquired; this process phase is called core acquisition (Baballe et al., 2023). Then, it is disassembled into various components. All its components are evaluated strictly to assess their state and potential to be reused. After cleaning them to remove impurities, repairs or replacements are made where necessary. This is also the stage where

functionality can potentially be advanced beyond what it initially had (King & Gu, 2010). In the next stage, the components are put together into fully functional products that undergo testing to establish standards of quality (Baballe et al., 2023). After the verification, the products are reintroduced back into the market, extending their cycle of service. This circle is completed when the products are eventually returned to be remanufactured once again, as an ongoing sustainability practice.

3.2 Environmental Impact of Remanufacturing

Compared to manufacturing new products, remanufacturing has a significantly lower environmental impact, though it is important to note that it still contributes to environmental degradation (Dias et al., 2013). Environmental impacts associated with diesel engine remanufacturing identified that the manufacturing of new parts for replacement has the highest environmental impact within the remanufacturing process (Zheng et al., 2019). Manufacturing new parts to replace worn-out or damaged parts increases huge environmental impact, evidenced by their substantial contributions across many categories of impacts. These categories include such as Eutrophication Potential (EP) – causing nutrient pollution leading to algae growth, Global Warming Potential (GWP) – affecting climate change due to greenhouse gases, Acidification Potential (AP) – emissions causing soil and water acidification, Respiratory Inorganics (RI) – particulates impacting respiratory health, Potential Energy Demand (PED) – demand for non-renewable energy, and Abiotic Depletion Potential (ADP) – depletion of non-renewable resources (Zheng et al., 2019; Simonen, 2014). The study by Zheng et al. (2019) investigated the environmental impact of different phases of the remanufacturing lifecycle. Production of new components for replacement has the greatest environmental impact. In contrast, disassembly, cleaning, and inspection contribute less to these impacts.

Remanufacturing greatly conserves materials and energy, resulting in substantial environmental benefits (Duflou et al., 2006). However, the environmental benefits of remanufacturing depend on several factors such as the design of the product. If a product is not designed for remanufacturing, it may have a harder process and therefore affect the overall benefits. Logistical factors, such as the transportation of products over longer distances to the remanufacturing sites, increase emissions and diminish the positive impact of remanufacturing. Another study highlighted similar factors, explaining that durable mechanical components are more easily remanufactured, while others may become outdated with advancements in electronic technology (Sundin & Lee, 2012). System boundaries or the scope of the analysis also have an effect. Analyses that

include transportation, use, and disposal phases may show different environmental impacts than analyses that consider only the manufacturing phase. In addition, the methodology and assumptions of the environmental analyses, regarding whether to include the use phase, can lead to differing conclusions. Technological advances, such as energy efficiency in newer models can reduce the environmental advantages of remanufacturing older models.

3.3 Environmental and Economic Benefits of Remanufacturing

This chapter discusses how remanufacturing is affecting the economy and the environment. The case studies explore the efficiencies of remanufacturing practices in reducing the environmental footprint and improving economic efficiencies across the diesel engine, diesel motor, and automotive industries. All case studies utilized LCA to evaluate environmental impacts and the results are compiled in Table 1.

In the case of a diesel engine remanufacturing process, it still required considerable resource consumption and emitted emissions, even though the amount of energy and raw materials were conserved compared to new manufacturing (Dias et al., 2013). The process required 590 kg of coal and 49 kg of crude oil, representing a reduction of 73% and 18%, respectively. Moreover, remanufacturing required 3 620 MJ of energy, showing a 39% reduction compared to the 6 016 MJ needed to manufacture a new engine. Emission of CO_2 during the manufacture of a remanufactured diesel engine was 1 ton, and 4 tons for a new engine, accounting for a reduction of 74%. Among the water emissions resulting from remanufacturing were Chemical Oxygen Demand (COD) and Ammonium (NH_4) and the reductions in those emissions were 92% and 74%, respectively.

In the case of other remanufactured diesel engines, CO_2 emissions were reduced by 74%, while SO_2 emissions dropped by 21% and NOx emissions by 60%. Other emissions included a 69% decrease in CH_4 and a 48% reduction in CO. Energy consumption decreased by 66%. Regarding material consumption, there was a 74% reduction in coal, an increase in crude oil usage by 36%, and a 71% reduction in natural gas. Water pollutants, including COD, were reduced by 82%, while NH_4 emissions dropped by 60%. This study also evaluated cost impact, which was 50% lower than the newly manufactured diesel engines. Similarly, the remanufactured cylinder heads showed a 67% reduction in CO_2 eq, while CO_2 emissions were reduced by 76%, SO_2 emissions decreased by 66%, and NOx emissions were reduced by 52% (Liu et al., 2014). Other emissions included a 69% reduction in CH_4 and a 48% decrease in CO. In terms of

material consumption, there was a 78% reduction in hard coal, while crude oil usage increased by 43%, and natural gas consumption decreased by 59%. Water pollutants were also reduced, with COD emissions dropping by 89% and NH_4 emissions by 46%. The study also mentioned a significant reduction in material and costs.

Table 1 *Case studies comparison*

Environmental Impact Difference	Cost Impact	Case Study
CO_2 Emissions Reduction: 74% **SO_2 Reduction:** 71%, **NOx Reduction:** 62% **Other Emissions:** Reductions in CH_4 by 31%, and H_2S by 98% **Energy Consumption reduction:** 40% **Material Consumption:** Reduction in Coal by 73%, reduction in Crude oil by 19%, and reduction in Nature Gas by 69% **Water Pollutants Reduction:** COD by 92% and NH_4 by 74%	Significant reduction in energy and material costs	(Dias et al., 2013) Case: Remanufactured Diesel Engines
CO_2 Emissions Reduction: 74% **SO_2 Emissions Reduction**: 21%, **NOx Emissions Reduction**: 60% **Other Emissions:** Reductions in CH_4 by 69%, and CO by 48% **Energy Consumption Reduction**: 66% **Material Consumption:** Reduction in Coal by 74%, **increase** in Crude Oil by 36%, and reduction in Nature Gas by 71% **Water Pollutants Reduction**: COD by 82% and NH4 by 60%	Overall reduction in cost: 50%	(Liu et al., 2014) Case: Remanufactured Diesel Engines
CO_2 Equivalent Reduction: 67% **CO_2 Emissions Reduction:** 76% **SO_2 Reduction:** 66%, **NOx Reduction:** 52% **Other Emissions:** Reductions in CH_4 by 69%, and CO by 48% **Material Consumption:** Reduction in Hard Coal by 78%, **increase** in Crude Oil by 43 and decrease in Nature Gas by 59% **Water Pollutants Reduction:** COD by 89% and NH_4 by 46%	Significant reduction in energy and material costs	(Liu et al., 2016) Case: Remanufactured Cylinder Heads

All three case studies showed considerable environmental and economic benefits of remanufacturing across two industries. In all three cases, remanufacturing was found to have considerable reductions both in energy and emissions and significant savings in material usage compared with new manufacturing processes. For the two diesel engine case studies, the reduction ranged from 67% to 74% in CO_2 emissions and material usage, such as coal and crude oil. The pollutants in water, such as COD and NH_4, also showed great reductions, indicating huge environmental benefits. All the cases showed economic advantages for cost reduction, with one as high as 50%, proving that remanufacturing is far more viable financially than new manufacturing. These consistent environmental impacts among the cases reinforce the positive impact of remanufacturing on sustainability.

Remanufacturing has a massive role in the CE model associated with sustainability (Van Loon & Van Wassenhove, 2018). It not only helps conserve resources but also reduces environmental degradation to a large extent by reducing waste generation. Remanufacturing prolongs the product's life with enormous energy savings and reduced emissions (Butzer & Schötz, 2016). It supports economic growth and provides highly skilled jobs. By increasing the life cycle of already used materials and products, remanufacturing is an effective way to attain resource efficiency and related economic savings. Higher remanufacturing yields lead to higher environmental benefits (Van Loon & Van Wassenhove, 2018). Higher remanufacturing yields have considerably less CO_2 emission, providing evidence of how remanufacturing might improve sustainability in manufacturing processes.

An LCA study on remanufactured engines indicates excellent environmental and economic benefits (Smith & Keoleian, 2004). According to the research, remanufactured engines consume 68% - 83% less energy than new engines and reduce CO_2 emissions by 73% -87%. Other air emissions also showed a considerable reduction, including Carbon monoxide (CO) by 48% - 88%, Nitrogen oxide (NOx) by 72% - 85%, Sulfur oxide (SOx) by 71% - 84%, and Nonmethane hydrocarbon emissions by 50% - 61%. Raw materials usage is reduced by 26% to 90%, while solid wastes are generated less by 65% - 88%. Remanufacturing not only helps to reach the objectives of environmental policy but also enables very cost-friendly solutions and provides both producers and consumers with a valid economic alternative. The economic analysis also brings out the cost-benefit that places consumers at saving between 30% and 53% by using remanufactured engines, with maximum savings when buying directly from a remanufacturer. The study goes on to add that remanufacturing reduces labour costs

drastically, saving about 67% as compared to conventional manufacturing methods. The cost-effectiveness is attributed primarily to operations running smoothly in full-service machine shops specializing in remanufacturing.

A study by Zheng et al. (2019) outlines a range of savings across different impact categories when comparing remanufacturing to new manufacturing. This scenario represents conventional practices to repair engines and shows considerable environmental improvements. Table 2 shows that the Eutrophication Potential has the highest reduction, about 87%, indicating a huge reduction in the potential for nutrient enrichment of receiving waters (leading to harmful algal blooms). This is followed by GWP, which goes down by 77%, thus pointing to a significant reduction in GHG emissions.

Acidification Potential and Respiratory Inorganics both see reductions of 76% and 75% respectively, which suggests a notable decrease in emissions that contribute to acid rain and airborne particulates affecting respiratory health. Similarly, the Potential Energy Demand is reduced by 75%, indicating reduced energy consumption throughout the remanufacturing process. Abiotic Depletion Potential is less affected but still reduced by 59%. Abiotic depletion is a measure of the consumption of non-renewable resources. At the other end of the scale, Water Usage has the most minor reduction at 19%, showing some savings in water consumption. In relative terms, this area has the most minor improvement of the categories measured. These results underscore remanufacturing for engines and their environmental benefit, which forecasts massive reductions in various forms of environmental impacts.

Table 2 *LCIA results of remanufacturing compared to new manufacturing (Zheng et al., 2019)*

Environmental Impact Category	Reduction Percentage
Eutrophication Potential (EP)	87%
Global Warming Potential (GWP)	77%
Acidification Potential (AP)	76%
Respiratory Inorganics (RI)	75%
Potential Energy Demand (PED)	75%
Abiotic Depletion Potential (ADP)	59%
Water Usage (WU)	19%

Remanufacturing also offers a significant economic gain (All-Party Parliamentary Sustainable Resource Group, 2014; Lavery et al., 2013). Input costs for producing remanufactured products, which are then sold at a 20% discount, are much lower than the input costs for manufacturing new products from virgin resources. Also, remanufacturing of leased products yielded the highest gross profit when compared with the gross profit of the manufacture of products from virgin resources.

Lavery et al. (2013) provide a conservative estimate of about 34% net reduction in input costs. With lower input costs and more significant labour spending, there still can be up to a 50% rise in gross profit. On the other hand, the study by Van Loon & Van Wassenhove, (2018) highlighted that remanufacturing becomes economically viable only when the cost of obtained used products (cores) stays under €30. Once this threshold is exceeded, remanufacturing costs exceed the new manufacturing cost. Yield rates also play a crucial role, as higher yields lead to lower costs. While optimized designs for remanufacturing offer some savings, the benefits are minor, and the overall cost savings from remanufacturing remain limited. Small reductions in disassembly and refurbishment costs cannot offset the higher production expenses, and the lack of large-scale production advantages continues to challenge remanufacturing profitability.

3.4 Operational Challenges and Barriers to Remanufacturing

The challenges of the remanufacturing process are mainly in three main areas; technical, economic, and logistical (Andrew-Munot & Ibrahim, 2013; Mohamed Nasir et al., 2021). One of the major challenges is acquiring used products that are suitable for remanufacturing, where both quantity and quality may have inconsistencies. The disassembly and condition assessment process requires special knowledge and tools that are both expensive and time-consuming. On the other hand, technical information on third-party products is rarely available, making the tasks of disassembly, repair, and reassembly by (OEM) standards very difficult (Parker et al., 2015).

In addition, to ensure that remanufactured products would be of similar quality to new products, high technology, and stringent quality control would be inevitable (Mohamed Nasir et al., 2021; Baballe et al., 2023). A wide range of returned products are of different types, thereby making it very difficult to standardize remanufacturing processes. Another problem is the poor product design, especially when remanufacturing has not been integrated into the business model of the OEMs (Parker et al., 2015). This results in increased costs and complexities. Technological advancements also mean that

remanufacturing methods and processes need constant upgrading to meet functionality and performance standards, particularly in industries like electronics.

Additionally, the collection, storage, and travel of used products are usually logistically demanding and can improve or decrease the efficiency and effectiveness of remanufacturing (Seitz & Peattie, 2004； Golinska-Dawson & Pawlewski, 2015). Companies will have to cope with the competition in acquiring old engines from external sources, and sometimes spare parts from internal sources, making its supply chain complex in remanufacturing management. A frequent lack of forward vision from designers can also be observed about how new engines can be adapted to remanufacturing needs. The used products often cannot seamlessly close the loop and re-enter the production cycle at the end of their life. It is hard to adapt the current logistic operations to handle reverse flows of used products, but it can be done, involving strategic changes in traditional supply chain operations.

The study by Rönkkö et al. (2021) has effectively compiled all the significant challenges of remanufacturing together incorporating insight from multiple sources to develop a proper review. These include issues with marketing remanufactured products such as overcoming the growing disposable culture and customer demands for newness (Thierry et al., 1995; Ijomah et al., 2007b; Saavedra et al., 2013). Other challenges include legislative issues, including environmental legislation, such as the prohibition of importing cores and remanufactured items into a country, which may restrict business operations (Zhang et al., 2021; Ijomah et al., 2007b). In addition, there are difficulties with the pricing model, more specifically with setting competitive pricing for remanufactured products in a market that often favours new over reused (Saidani et al., 2020). These specific challenges are crucial for understanding the broader regulatory and market dynamics that can obstruct the progress of remanufacturing initiatives (Rönkkö et al., 2021).

Chapter 3 elaborated on the remanufacturing process, demonstrating a reduction in its environmental impacts, and discussing economic benefits with respective case studies. The operational challenges were also dealt with, underlining the huge savings in energy and resources associated with the remanufacturing of industrial equipment such as diesel engines and auto parts. Though these technical and environmental successes do occur, the wider adoption of remanufacturing practices is not based on their feasibility alone but is significantly influenced by the perceptions of the market towards such practices. Chapter 4 therefore investigates the nature of market dynamics influencing the adoption of remanufactured equipment. It will assess consumer and industry perceptions

driving the acceptance of remanufactured products and seek to close the gap between remanufacturing capabilities and market adoption. This analysis is important for understanding the barriers to, and opportunities for, broadening this industry in remanufacturing.

4. MARKET PERCEPTIONS OF REMANUFACTURED EQUIPMENT

4.1 Market Dynamics of the Remanufacturing Industry

The remanufacturing industry accounted in 2017 for about 2% of the total manufacturing in Europe, producing revenues of around €30 billion annually (Figure 3) (Lange, 2017). This turnover is primarily brought by industries such as aerospace, automotive, and electrical and electronic equipment, including heavy-duty and commercial vehicles. Germany leads the market in both turnover and in number of company headquarters and remanufacturing facilities. Geographically, Germany, the United Kingdom, Ireland, France, and Italy are the key players, generating more than two-thirds of the European turnover. Companies based in Germany account for approximately one-third of the total remanufacturing turnover. The European remanufacturing market consists mainly of micro-enterprises and small enterprises that are essentially independent remanufacturers.

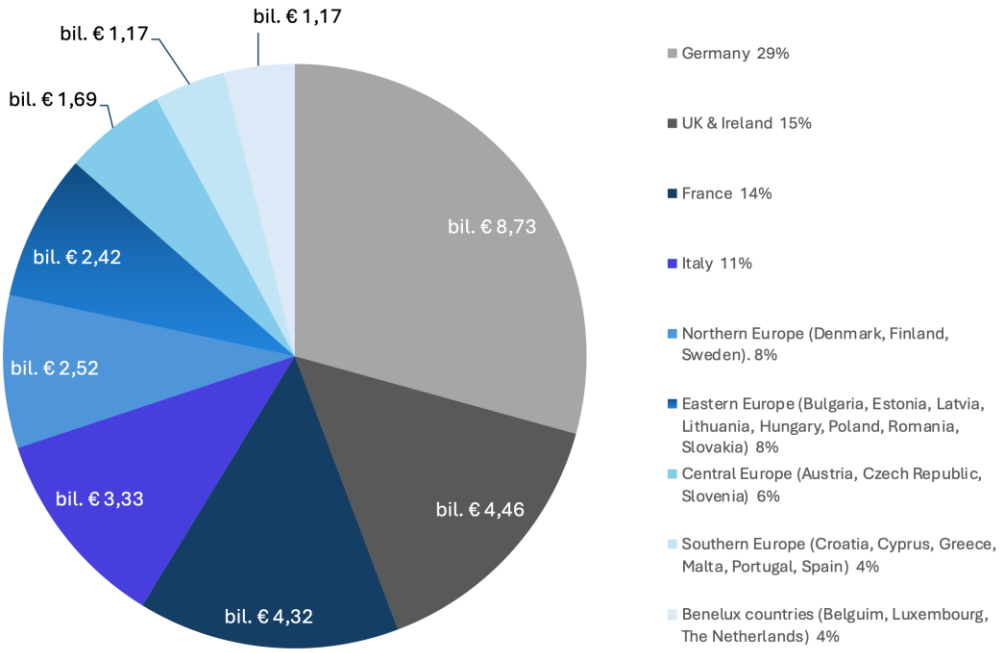

Figure 3 *Remanufacturing industry turnover by country (Adapted from Lange, 2017)*

The administration of acceptance for remanufactured industrial equipment considers critical market dynamics (Milios & Matsumoto, 2019). Market acceptance seems to be

influenced by customer perceptions, as most consumers associate remanufactured products with lower quality and reliability than new equipment. According to Milios & Matsumoto (2019), there is bias in consumer perception towards the remanufactured components of automobiles, this could also be true for industrial equipment. Many consumers question the durability and performance of used equipment, often believing that a second-hand device may have a shorter lifespan than a new one. This is supported by another study, which says that perceived risk related to the failure of products massively affects plans for purchasing remanufactured products (Chen et al., 2019). Remanufactured equipment is usually less expensive than new ones, making cost vital from a reduced price. This perception problem is also mentioned in other findings, which have established that even when setting a lower price for remanufactured products, consumers were still willing to pay more for new items due to concerns about quality and durability (Michaud & Llerena, 2011).

Changes in environmental regulations have influenced the remanufacturing industry significantly (Abbey et al., 2015). Strict environmental-related regulations would make businesses take up the aspects of remanufacturing as an alternate method for adhering to environmental standards, thereby promoting the company associated with the remanufacturing industry. Government incentives and subsidies also promote it through advising on remanufacturing (Singhal et al., 2019). Financial incentives through tax breaks, subsidies, or rebates lower the overall cost of remanufactured products, increasing their appeal to consumers. Moreover, the incentive policies and regulatory efforts improve the quality of remanufactured products (Chen et al., 2019). It also makes tremendous progress in quality control and continuous technological improvement for remanufactured products to become end-use comparable with their new counterparts in performance and reliability. This enhances customer confidence and increases willingness to buy remanufactured products because they are perceived to be at least equally reliable and long-lasting alternatives. Furthermore, the well-arranged distribution channels and strong returns policies also reduce consumers' perceived risks while buying remanufactured products (Confente et al., 2021). The companies providing generous return policies assure their consumers about the quality of these products, encouraging them to make more purchases. The well-organized distribution channel channels make the products easily accessible to consumers, increasing their attractiveness.

4.2 Role of Technology and Innovation in Remanufacturing

Technological innovations associated with Industry 4.0, also known as the fourth industrial revolution significantly influence the remanufacturing industry (Yang et al., 2018). Among them are smart sensors and Internet of Things (IoT) functionalities that provide real-time monitoring and control of remanufacturing processes, improving operational efficiency and predictive maintenance (Lu, 2017; Yang et al., 2018). Computational and physical processes are integrated using Cyber-Physical Systems (CPS), guaranteeing a seamless workflow and greater adaptability in remanufacturing environments (Yang et al., 2018). Furthermore, Artificial Intelligence (AI) and machine learning algorithms optimize decision-making procedures for improved quality control, waste reduction, and better resource management.

Figure 4 provides the holistic picture of what Industry 4.0 brings to the processes toward the betterment of remanufacturing. It shows the three application areas and technical enablers according to the Industry 4.0 model (Yang et al., 2018). Outer rim circle technology enablers include intelligent sensors, cloud computing, robotics, machine-to-machine communication (M2M), additive manufacturing, and others. Monitoring tools are needed for constant follow-up data capture for optimization in process operations, while control systems automate and adjust these operations. Non-Destructive Testing (NDT) guarantees the integrity of the component to be used without damaging it and is thus crucial for quality assurance (Yang et al., 2018; Medici et al., 2023).

Smart sensors gather relevant real-time data, therefore complementing the monitoring and control processes (Yang et al., 2018). Smart logistics enables smooth material flow with reduced operational costs. Cloud services provide variable computing and storage solutions — critical in handling big datasets. Additive manufacturing, also known as 3D printing, allows for making parts for specific defects and accurately to size – reducing scrap (Yang et al., 2018; Lahrour & Brissaud, 2018). Safety schemes that ensure sensitive operational information do not become public; machine-to-machine communication is a concept whereby devices automatically and efficiently communicate with one another (Yang et al., 2018). Robotics allows for precision and efficiency in repetitive tasks; Human-Machine Interfaces (HMI) make user-friendly communication with this automatic apparatus feasible (Yang et al., 2018; Bryksin et al., 2023). Finally, smart mobility technologies raise the efficiency of goods and personnel movement within facilities to allow flexibility and responsiveness during manufacturing workflows (Yang et al., 2018). All these technologies can substantially improve the efficiency, quality, and sustainability of remanufacturing processes.

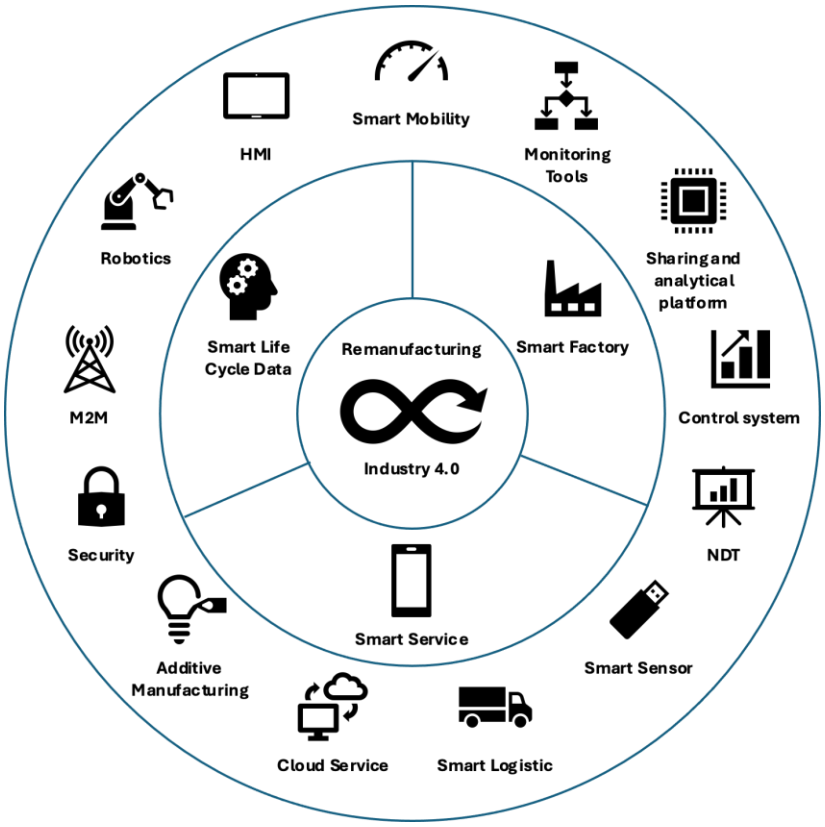

Figure 4 *The potential of Industry 4.0 for remanufacturing and its essential enablers (Yang et al., 2018)*

Innovative coating technologies and laser cladding techniques are changing the metallurgical industry by making it greener and more efficient (Xiong et al., 2016). Nano-material coatings improve the durability and lifespan of remanufactured components by providing better resistance to abrasion, corrosion, and thermal wear (Xiong et al., 2016; Gu et al., 2020). Similarly, laser cladding helps restore dimensions and properties without causing extensive heat damage (Xiong et al., 2016; John et al., 2022). The technique involves a focused laser beam that accurately projects the material onto worn or damaged areas, ensuring accurate restoration with minimal disturbance of the base material. This form of precision does not only reinstate functionality but also secures and saves the integrity of the original component (Xiong et al., 2016). This approach offers many cost-effective solutions for extending the working life of high-value parts and supporting environmental goals by reducing waste and energy use.

A study by Zheng et al. (2019) has compared traditional engine remanufacturing to advanced technologies used for remanufacturing engines utilizing LCA methodology. The study used advanced methods such as brush electroplating, arc spraying, and laser cladding. These techniques not only restore damaged components to their original

specifications but also improve their material properties with enhanced strength, wear, and corrosion resistance. Other methods, such as brush electroplating, were used for surface property improvement, while innovations like automatic nano-brush electroplating have improved consistency and throughput. Arc spraying reduces remanufacturing times down to 20 minutes, with a minimum material use of just about 3% needed to build a new part, while laser cladding provides very effective precision with minimal waste, ideal for complex parts like heavy-duty gears and aluminium alloy cylinder heads. Compared to traditional processes, advanced technologies slightly reduced GWP by 0.2%, Energy Demand by 0.3%, and Resource Depletion by 0.9%, but increased Water Usage by up to 2.6%. These advanced technologies align with environmental sustainability goals by reducing material waste and decreasing energy consumed in the remanufacturing process.

5. METHODOLOGY

The study analysed environmental footprint calculations and cost efficiencies for both new and remanufactured SS tanks, along with exploring market dynamics, such as supply, demand, and industry feedback through a questionnaire-based survey. LCA methodology was applied to compare the environmental impacts from raw material extraction to the delivery of the tanks at the installation site, excluding the use phase and EoL processes. The research scope included cost-effectiveness and market involvement based on the feedback from industrial stakeholders.

The storage tanks analysed in this thesis are used for storing liquids, gases, and hazardous chemicals in industrial applications, such as refineries and chemical plants (Huang & Mannan, 2013; Chang & Lin, 2006). Storage tanks are usually made from material having resistance to the corrosive or reactive properties of the stored chemicals (Myers, 2000). Commonly used materials include SS, carbon steel, reinforced concrete, and different plastics such as polyethene and fibreglass-reinforced plastic.

5.1 LCA of Stainless Steel Chemical Storage Tank

5.1.1 Goal and Scope

The goal of the study was to compare the environmental impacts of new versus remanufactured SS chemical storage tanks, in terms of environmental footprint. The LCA aimed to compare the environmental impacts of a 100m³ SS chemical storage tank, focusing on both new and remanufactured options. The study examined life cycle stages, including raw material extraction, production, manufacturing processes and remanufacturing processes. It also explored opportunities to reduce resource consumption and emissions.

The LCA evaluated the cradle-to-gate life cycle of both new and remanufactured tanks. This included raw material extraction (Fe, Cr, Ni), SS production, tank manufacturing processes (cutting, welding, assembly), surface treatments (painting and passivation), transportation to Finland, and the installation and use phases. However, EoL processes like recycling and disposal were excluded as the focus is on comparing the environmental impacts of new and remanufactured equipment during production processes. For the remanufactured tanks, the analysis focused on disassembly, cleaning, repairing, and reassembling. The functional unit for both assessments was one

100m³ SS tank used for chemical storage, excluding office operations and insignificant packaging based on cut-off criteria. Cut-off criteria define the amount of energy flow, material, or environmental impact that could be excluded from a study (ISO 14044, 2022). It sets a threshold, allowing certain data to be excluded if its impact on the overall study results is minimal. Similar to the new tanks, the use phase and EoL stages are excluded from the analysis. A study by Zheng et al. (2019) took a similar approach and reasoned that these phases were excluded so that the production and restoration processes may be focused on since they provide a more significant comparison of environmental impacts in remanufacturing.

The system boundaries (Figure 5) for this LCA used the cradle-to-gate stages for both new and remanufactured SS tanks. For the new tanks, this included raw material extraction, material processing, fabrication, assembly, surface treatment, finishing-packaging, and transportation to the installation site.

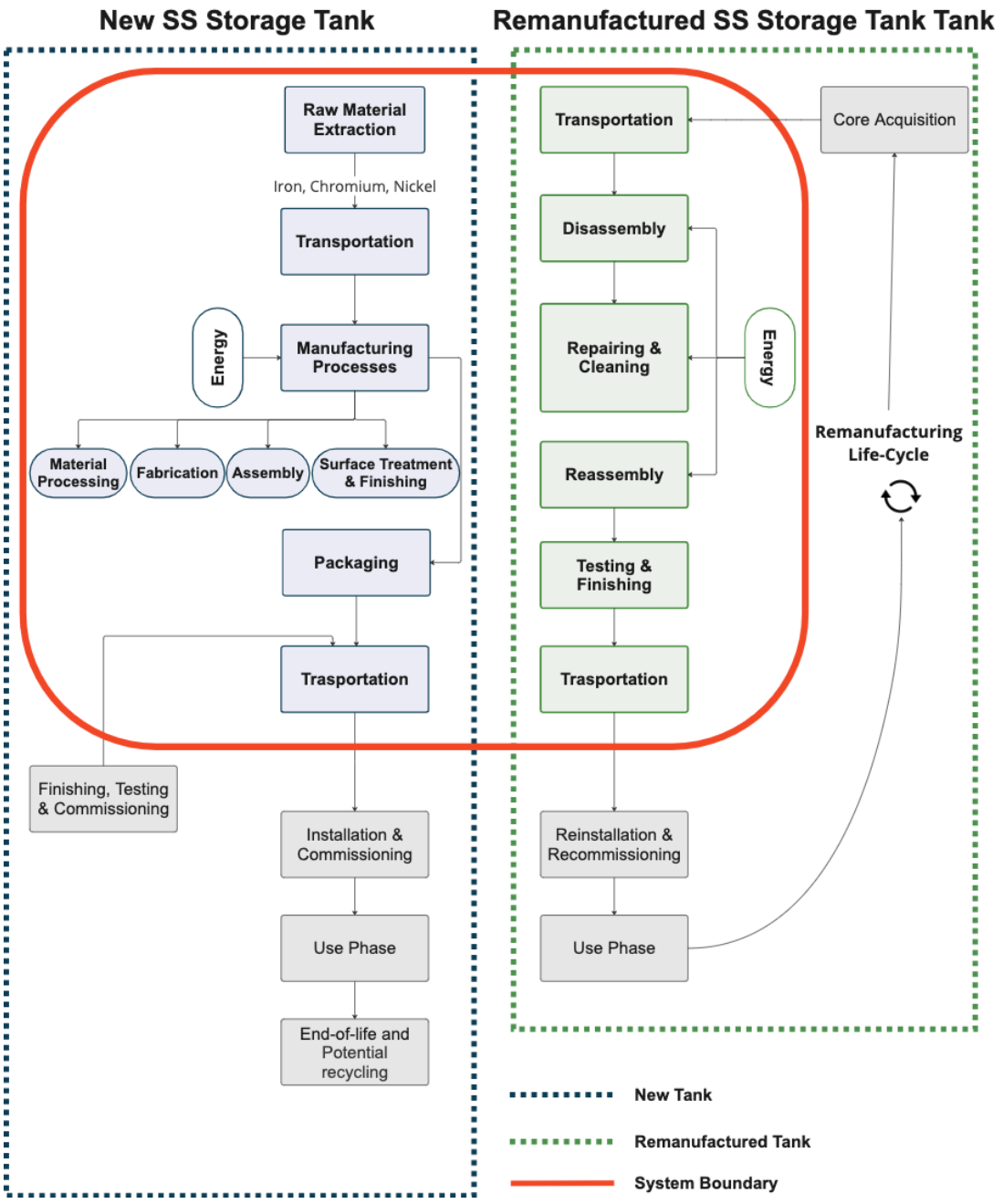

Figure 5 *System boundary*

The system boundary for remanufactured SS tanks included the core acquisition, disassembly, repair, cleaning, reassembly, testing, transportation to the remanufacturing site, and transportation of the finished tank to the site. No packaging was considered for the remanufactured SS tanks, as it was assumed no packaging was required. Both system boundaries considered energy consumption and material flows associated with production, remanufacturing, and transport stages, ensuring consistency in comparing the two approaches. The study used the Environmental Footprint (EF) 3.1 method that aligns with EU policies for the analysis of LCA. The impact categories were chosen

based on the study's requirements which were climate change, climate change - biogenic, climate change - fossil, resource use - fossils, resource use - minerals and metals, and water usage.

5.1.2 Data Collection and Inventory

The case study was to compare the environmental impacts of new and remanufactured SS storage tanks covering the stages from raw material extraction, energy consumption, and transportation. However, the use phase and disposal at the end of the tank's life are excluded to concentrate on the impacts leading up to the installation. A 100 m³ in volume, weighing 6 300 kg, SS storage tank, as recommended by Rejlers Finland, serves as the functional unit to ensure a consistent basis for comparison (Figure 6). The tank in question is 8 m in height, 4 m in diameter, and with a thickness of 0.005 m for shell plates, bottom plates, and roof plates.

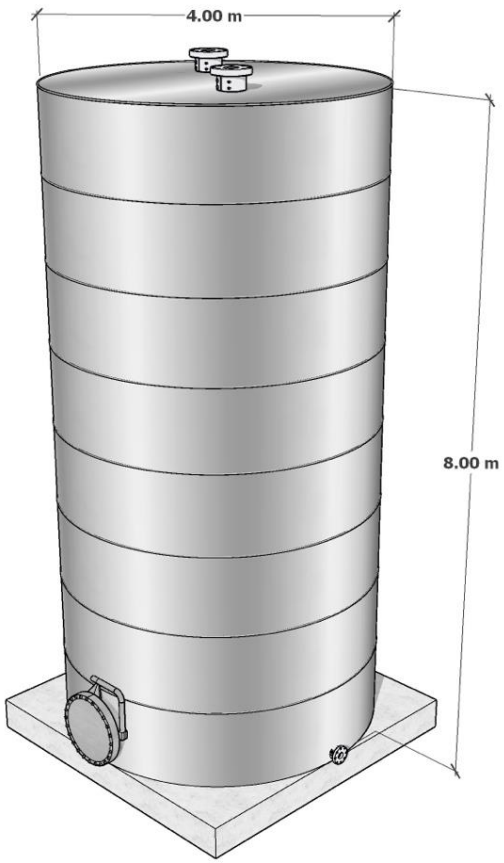

Figure 6 *Austenitic SS tank*

Data for the new SS storage tank was gathered from secondary sources, including Johnson et al. (2008) for raw material composition (Fe 74%, Cr 18%, Ni 8%). The

inventory for the LCA is presented in Table 3. SS production followed the SFS 14015 standard for EN 1.4404 austenitic SS, confidential client data (SFS-EN 14015, 2005), and actual European site distances. Calculations done in SimaPro were based on Ecoinvent 3.10 data processes complied in 2024. The weight of the casting steel is based on the standard size acquired from Rejlers Finland. Electricity consumption for both tank types was modelled with SimaPro, based on the Ecoinvent European energy mix and global energy data, prioritizing European sources when available. Electricity usage was calculated based on the weight of the tank and the standard consumption of machines such as the strapping machine, wrapping machine, sanding equipment, and pumping for hydrostatic testing, as well as ultrasonic and radiography testing, used in the processes of both new and remanufactured tanks. Packaging was calculated based on the height, diameter, and radius of the tank using standards used by Plastic Europe (Plastics Europe, 2021). The steel straps and wooden pallets were estimated based on typical requirements for the tank in question, and this information was sourced from relevant websites. For the remanufactured tanks, data were gathered through primary observations, estimating transportation at 500 km, roughly half the length of Finland. Water usage was calculated using methods described by SPX Corporation (2013) for cleaning and repair processes, and Harry et al. (2021) methods for three rinse cycles during cleaning, repair, testing, and finishing. Unlike the new tanks, the remanufactured tanks required no packaging. The surface repair was calculated based on the weight of a 1x2m recycled SS used with a thickness of 0.005m, weighing 80 kg, along with an additional 20 kg for the manhole flange repair, following the SFS 14015 standard for EN 1.4404 austenitic steel (SFS-EN 14015, 2005).

Table 3 *New and Remanufactured SS Tank Inventory*

New SS Tank Inventory			
Material and Process	**Amount**	**Unit**	**Sources**
Iron (Fe) 74%	3719.65	kg	Johnson et al. (2008)
Chromium (Cr) 18%	904.78	kg	Johnson et al. (2008)
Nickel (Ni) 8%	402.12	kg	Johnson et al. (2008)
Casting, steel	6300	kg	Weight of the studied SS tank
Energy and auxiliary inputs, metal working factory	6300	kg	Calculated based on the weight of the studied SS tank with selected energy input mode from SimaPro for Metalworking factory
Packaging film, low-density polyethylene	10	kg	Plastics Europe (2021)
Transport, freight train	4765.17	tkm	Estimated based on actual European site distances
Transport, freight, lorry 16-32 metric ton	5271.20	tkm	Estimated based on actual European site distances
Transport, freight, lorry 3.5-7.5 metric ton	1260.00	tkm	Estimated based on actual European site distances
Wood Pallet	200	kg	Estimated based on typical requirements for studied SS tank packaging
Remanufactured SS Tank Inventory			
Electricity, medium voltage	19800	MJ	Calculated based on the weight of material needed for repair
Metalworking, average for steel product manufacturing	100	kg	Weight of the material needed for repair
Transport, freight, light commercial vehicle	6300	tkm	Weight of the studied SS tank
Water Usage	144	m^3	SPX Corporation (2013), Harry et al. (2021)
Welding, arc, steel	5	m	Calculated based on the surface area of the material needed for repair
Welding, gas, steel	6	m	Calculated based on the surface area of the material needed for repair

One of the limitations of this study was the use of secondary data for certain material inputs and processes, particularly for SS production and electricity usage. Although European data were preferred, gaps in the Ecoinvent database necessitated the inclusion of global energy data, which may reduce the geographical accuracy of the findings. Furthermore, the inclusion of confidential information in the SS modelling limits

data transparency. Assumptions regarding transportation distances, particularly for the remanufactured tanks, also may have presented some uncertainty, potentially affecting the overall environmental impact results.

5.2 Market Analysis

The market analysis in this study was conducted using two main approaches: secondary research and primary data collection. Secondary research involved the review of existing literature, industry reports, and case studies to assess trends, pricing, and the competitive landscape within the remanufacturing industry. The study gathered primary data from industrial stakeholders through a questionnaire-based survey to capture market perceptions and potential barriers to the adoption of remanufactured products. Additionally, a cost analysis was performed to compare the economic benefits of remanufacturing versus new production, providing a comprehensive understanding of market dynamics and the economic potential of remanufactured equipment.

To understand the market dynamics of remanufactured industrial equipment a questionnaire-based survey was conducted with eight participants of Rejlers Finland's clients (Rejlers Finland Oy, 2024). The participants represented industries such as manufacturing, technology, and energy. The diversity in industries increases the reliability of the data and to understanding the broader market perspective. In order to provide a thorough analysis, the survey questions were designed to gather both quantitative and qualitative data. The survey was done anonymously, and no personal data was collected. It aimed to evaluate respondents' familiarity with remanufactured industrial equipment, interest, current procurement practices, and the factors that might influence the decision to opt for remanufactured products. The questionnaire-based survey (Appendix A) addressed several critical aspects of market dynamics such as performance reliability, economic and environmental benefits, and perceived obstacles to adoption.

This thesis conducted a cost analysis to evaluate the economic implications of remanufacturing compared to producing new industrial equipment, with a particular focus on SS storage tanks. The analysis calculated the total costs associated with both manufacturing and remanufacturing processes, focusing on material costs, labour, and energy consumption.

Data for this analysis was sourced from secondary materials, including industry standards, case studies, and data provided by Rejlers Finland. The methodology

acknowledged key cost components such as material, manufacturing processes, and operational expenses for both new and remanufactured equipment, presented in Table 4. Additionally, remanufacturing-specific cost-considering factors, such as disassembly, cleaning, and reassembly, were integrated to provide a comprehensive comparison. Materials have been described in chapter 5.2.2. Labour hours for both new and remanufactured SS tanks have been calculated based on the Technical Calculation and Estimator's Man-Hour Manual by Fardyanto (2003) and the Eurostat database (Eurostat, 2024).

Energy consumption values for manufacture were calculated using secondary sources Energy Consumption of Welding-Based Additively Manufactured Materials by (Raju et al., 2020). Remanufacturing energy consumption was estimated using sources Energy Consumption Assessment of Remanufacturing Processes by Li et al., (2013), and industry norms. Transportation distances were estimated using real site distances, considering relevant logistical routes, the Cost Model for Remanufacturing by Reddy Abbu et al., (2022), and average costs for transportation rates. Compliance costs were estimated based on the SFS 14015 standard, including non-destructive testing methods as indicated in the compliance guidelines. Surface treatment (pickling, passivation, and surface finishing) calculation for the new tank and repair and surface treatment for the remanufactured tank estimations were based on provided guidelines and treatment extent defined in SFS 14015, industry report by Staff (2017) and Cost Model for Remanufacturing by Reddy Abbu et al., (2022).

Table 4 *Data Sources for Cost Estimation of New and Remanufactured SS Tanks*

Component	New Tank	Remanufactured Tank	Source/Estimate
Material	6 300 kg of 316L SS	100 kg of Recycled SS	Details in Chapter 5.2.2
Labour	407 hours	357 hours	Fardyanto (2003), Eurostat (2024)
Energy	66 316.8 MJ (18,431 kWh)	15 140 MJ (4 206 kWh)	Raju et al. (2020), Li et al. (2013)
Transportation	12 114 km	1 000 km	Reddy Abbu et al., (2022)
Compliance	10 000 €	12 000 €	SFS 14015 standard
Surface Treatment	Coating and Polishing (Full Surface)	Repair and Partial Surface Treatment	SFS 14015 standard, Staff (2017), Reddy Abbu et al. (2022)
Water Usage	92 500 litres	1 290 litres	LCA data, Eurostat (2024)
Equipment & Tooling	1 200 € for cutting, welding, bending	10 000 € for disassembly and reassembly tools	Industry averages, Rent costs
Design & Engineering	CAD design, structural analysis		Estimation based on Industry standards
Overhead	Overhead = 25% of (Material Costs + Labor Costs + Energy Costs + Transportation Costs + Equipment & Tooling Costs + Water Usage Costs)		25% of direct costs for overhead expenses (estimated based on industry standards)
Profit Margin	Profit Margin = 15% of (Total Direct Costs + Overhead)		Estimation based on Industry standards
25.5% VAT	25.5%	25.5%	25.5% VAT applied on total cost

Water usage values were estimated based on LCA data, and the cost calculation was done based on average water cost in Europe. Equipment and tooling costs were calculated based on the average rent cost of equipment such as cutting, welding, and bending machinery. Design and engineering costs were estimated on industry norms. Overhead costs were estimated at 25% of the direct costs, using industry-standard estimates and the calculation of combined direct costs including material, labour, and energy. Profit margin was calculated at 15% of the total direct costs and overhead. 25.5% VAT was applied to the total costs as per the standard VAT rate used in the analysis based on industry and regional norms.

6. RESULTS AND DISCUSSION

6.1 Environmental Impact Comparison of New and Remanufactured Equipment

The comparison between new and remanufactured SS tanks revealed a reduction in environmental impacts of over 90%. The assessment revealed substantial differences across all impact categories, with remanufacturing consistently reducing environmental impact. Table 5 illustrates the comparison of new and remanufactured tanks and revealed differences in percentage calculated based on the absolute values of impacts between the new and remanufactured tanks.

The environmental impact analysis revealed a substantial difference in climate change effects between new and remanufactured SS tanks. The total climate change impact from producing a new tank was 261 000 kg CO_2 eq, shown in Table 5. The high value was mainly due to the processing of raw materials and extraction of them. The raw materials Fe, Cr, and Ni, each contributed to 389 kg CO_2 eq, 25 140 kg CO_2 eq, and 7 280 kg CO_2 eq, respectively. Each metal undergoes energy-intensive processes that significantly elevate GHG. Similarly, the large amount of the impact resulted from the production stage, primarily due to high energy demand and the associated emissions during the melting and refining processes in SS production. In comparison, the climate change effect of the remanufactured tank was far less, at around 13 200 kg CO_2 eq, reflecting a 95% decrease. The decrease is largely due to remanufacturing needing less energy and emitting lower emissions. By excluding energy-intensive stages like raw material extraction and primary metal processing, remanufacturing relies on reusing materials instead, leading to a notable decrease in the environmental footprint. The LCA results showed that remanufacturing had approximately 95% lower climate impact than manufacturing a new tank, highlighting a major environmental advantage over manufacturing new tanks.

Table 5 *Environmental Impact comparison of new and remanufactured SS storage tank*

Impact Category (Characterization)	New SS Tank	Remanufactured SS Tank	Differences
Climate Change (kg CO_2 eq)	261 000	13 200	95%
Climate Change - Biogenic (kg CO_2 eq)	9 090	14	99 %
Climate Change - Fossil (kg CO_2 eq)	251 000	13 100	95%
Resource use, Fossils (MJ)	3 340 000	187 000	94 %
Resource Use, Minerals and Metals (kg Sb eq)	3	0.11	97 %
Water Usage (m^3)	92 500	1 290	99 %

The biogenic carbon impact of the newly manufactured SS tank was 9 090 kg CO_2 eq. The emissions emitted during energy-intensive processes like the extraction and refinement of raw materials are the cause of this high value. By comparison, the remanufactured tank released 14 kg CO_2 eq, indicating substantially smaller biogenic emissions. This significant decrease is mostly due to the remanufacturing process using pre-existing materials and excluding the energy-intensive stages of new manufacture. Hence, as compared to the production of a new tank, the remanufacturing option reduced biogenic emissions by nearly 99%.

The climate change impact resulting from fossil fuel usage for the new SS tank contributed to 251 000 kg CO_2 eq. This considerable amount was mainly from the energy-intensive extraction and processing of raw materials, consuming large quantities of fossil fuels. The processes of heating, melting, and refining these materials require significant energy input, mainly from fossil fuel sources. Furthermore, transporting both the raw materials and the final product further contributed to fossil fuel emissions. These activities emitted a substantial volume of CO_2 into the atmosphere, significantly increasing the climate change impact associated with fossil fuel consumption. Comparatively, the remanufactured tank had a much less effect on climate change (13 100 kg CO_2 eq) due to fossil fuel use. The significant reduction was achieved through excluding many energy-intensive steps and reducing the use of fossil fuel-based energy. Remanufacturing eliminates the need for new raw material extraction and processing, which are the main causes of emissions from burning fossil fuels, by recycling existing resources. As a result, remanufacturing demonstrated its effectiveness in reducing fossil fuel use and related emissions, showing nearly a 94% reduction in climate change impact compared to constructing a new tank.

The production of a new SS tank consumed 3 340 000 MJ of fossil energy. This enormous energy demand comes from main production steps that heavily depend on fossil fuels, especially when it comes to extracting and refining materials. Transporting these metals and the finished tanks also added to the total energy use as manufacturing a new tank was incredibly resource-intensive. On the other hand, the remanufactured tank required only 187 000 MJ, resulting in a 94% lower energy demand compared to the newly manufactured tank. The major reduction in environmental impact is due to reusing materials and skipping energy-intensive extraction and refining. This aligns with the findings of Zheng et al. (2019), who reported a similar reduction in the energy demand of 93% for remanufactured engines compared to new ones.

The mineral and metal resource used for the new SS tank emitted 3 kg Sb eq of emissions. This high value mainly comes from the extraction and processing of rare metals like Cr and Ni, which are crucial for making SS. The energy required for mining and refining these elements is immense, and the environmental cost is equally high due to the emissions they produce. Cr and Ni have a particularly large impact because of their limited availability and the intensive processes needed to obtain them. In contrast, the remanufactured tank had an impact of only 0.11 kg Sb eq, a reduction of over 97 % due to no use of new material extraction, as the process used existing components. Remanufacturing not requiring additional mining or refining of these rare metals also reduces the demand for minerals and metals, making it a much more sustainable option for conserving crucial raw materials. The result achieved by Zheng et al. (2019) also showed that remanufactured engines had a reduction of 94% when it came to kg Sb eq associated with Abiotic Depletion Potential.

Water usage presented another critical environmental concern. Producing a new SS tank required approximately 92 500 m^3 of water, mainly due to the numerous water-intensive stages involved in production. These stages include ore processing, cooling, and cleaning operations during metal refinement, which collectively resulted in a significant water demand. Additionally, water is used for dust suppression and other secondary activities during the extraction and production of raw materials. In contrast, remanufacturing a tank required only 1 290 m^3 of water with a reduction of 99%. This drastic decrease is largely due to the elimination of primary metal extraction and the reduction of many water-heavy production steps. The remanufacturing process primarily used water for cleaning, repairing, and testing; this significantly reduced overall water usage. With fewer water-intensive processes and the reuse of materials,

remanufacturing illustrated advantages in water conservation compared to manufacturing a new tank (for detailed network diagrams, refer to Appendix B and C).

Figure 7 illustrates the relative environmental impact reduction achieved by remanufactured stainless steel (SS) tanks compared to new SS tanks across multiple impact categories. Each bar represents the impact of a new SS tank as the baseline (100%) in each category with the impacts of remanufactured SS tanks shown as a percentage of this baseline.

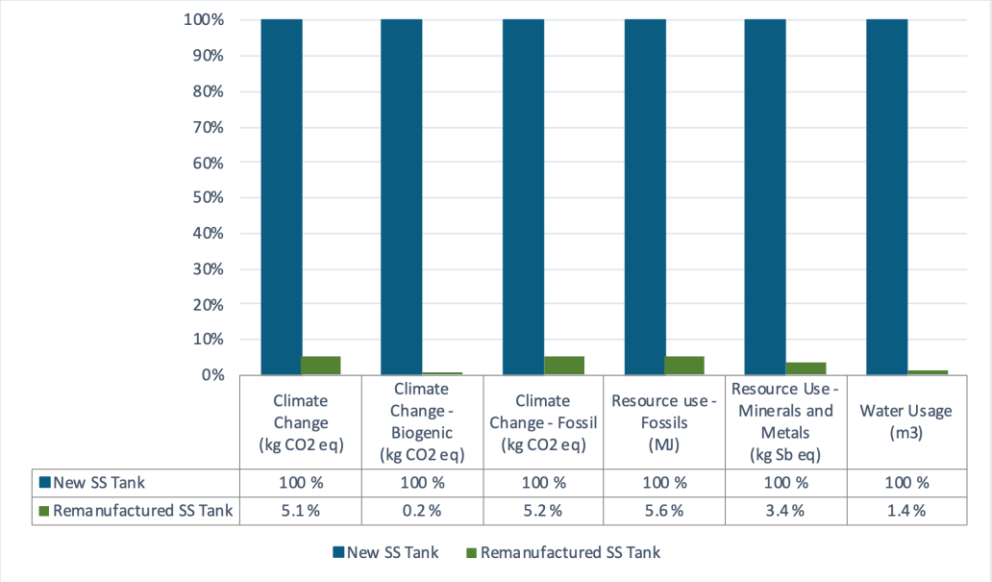

Figure 7 *Relative Environmental Impact Reduction in Remanufactured SS Tank*

The remanufactured tank showed substantial reductions in environmental impact compared to the new tank, contributing only 5.1% of the climate change impact, 0.2% of biogenic emissions, 5.2% of fossil fuel emissions, 5.6% of fossil resource use, 3.4% of mineral and metal resource use, and 1.4% of water usage compared to the new tank.

6.2 Economic Impact Comparison of New and Remanufactured Equipment

The economic comparison between the new and remanufactured SS tanks was carried out by considering the main cost component individually. Material, labour, energy, transportation, surface treatment, water consumption, equipment and tooling, design and engineering, overhead, profit margin, and VAT (Table 4) were all taken into consideration in the cost study. This was followed by the comparison of the total costs to determine

how economical the remanufacture processes were compared to the new manufacturing processes.

The cost of SS material for the remanufactured tank was much lower than for the new tank. This was mainly due to considerably less raw material needed for remanufacturing. Reusing existing materials instead of acquiring new SS resulted in significant cost savings, as shown in Table 6, with the material cost for the remanufactured tank being less than 1% of the cost for the new one. Labour costs were also lower for the remanufactured tank, though the reduction was not as significant as the material cost. However, compared to the new tank, the remanufacturing labour cost was approximately 12% lower. Similarly, energy costs on the remanufactured tank were much lower. Remanufacturing did not need the energy-intensive procedures needed for the original manufacture of SS.

As a result, remanufacturing energy costs were about 77% lower than manufacturing new tanks, emphasizing the advantages of remanufacturing for energy efficiency. The remanufactured tank also had much reduced transportation costs since the supply chain included shorter distances. Whereas the remanufactured tank entailed shorter logistical channels, the new tank needed transportation over larger distances for the delivery of the final product and the procurement of raw materials. Therefore, the transport of the remanufactured tank cost was approximately 65% lower than the cost of the new tank. However, this is an ideal scenario assumed for this case study, where the remanufacturing takes place in central Finland, making the distance to both the north and west approximately 500 km. As per the study by Parker et al. (2015), transportation can sometimes cause significantly higher costs, especially when transporting the product to another country for cheaper labour. In such cases, the costs would increase substantially, particularly for large or bulky items.

The remanufactured tank required compliance costs that were about 20% more than those of the new tank. The cost of complying with industry requirements for new tanks increased due to the need for more testing and quality control and to guarantee that the remanufactured tank met the same performance and safety requirements as the new tank. The remanufactured tank came with greater repair and surface treatment expenses. The remanufactured tank needed partial surface treatment, including repairs, whereas the new tank required complete surface painting and polishing. The specific methods required to restore the surface of the remanufactured tank resulted in three times higher total costs for these treatments compared to manufacturing a new tank. Additionally, remanufacturing tends to be more expensive due to the specialized nature

of the repair or replacement processes involved. Unlike the new tank, which follows the same standardized stages each time, remanufacturing requires addressing specific issues unique to each unit, making the process more manual and customized.

Water usage costs were reduced by 99% for the remanufactured tank compared to the new one. Remanufacturing excluded the water-intensive processes involved during the production stage. Equipment and tooling costs were 80% higher for the remanufactured tank. The new tank required conventional machinery for cutting, welding, and bending, which can be used repeatedly without modification, making the process more cost-effective. In contrast, remanufacturing required specialized tools for disassembly and reassembly, increasing the cost. Since remanufacturing did not involve redesign, only the new tank was subject to design and engineering cost calculations. The remanufactured tank had roughly 15% reduced overhead costs and lower profit margins due to decreased direct costs.

Table 6 *Cost comparison of new and remanufactured SS storage tank*

Cost Component	New Tank (€)	Remanufactured Tank (€)
Material	27 122	389
Labour	15 466	13 560
Energy	2 211	505
Transportation	3 634	1 260
Compliance	10 000	12 000
Surface Treatment	2 500	7 500
Water Usage	2 775	39
Equipment & Tooling	1 200	10 000
Design & Engineering	6 500	0
Overhead	13 250	11 250
Profit Margin	7 950	6 600
Subtotal	92 608	63 103
25.5% VAT	23 615	16 091
Total Cost with VAT	**116 223**	**79 194**

The cost analysis in this study indicated that this remanufactured tank was about 32% lower in cost than a new one, presenting economic advantages over the newly manufactured tank. This finding aligns with broader research indicating that remanufactured engines and parts typically cost 20–30% less than new ones, and the

overall cost savings from remanufacturing products can range from 30% to 70% (Simmons, 2013).

6.3 Market Perceptions of Remanufactured Equipment

The results of the questionnaire-based survey (Appendix A) were meant to understand the market perception about the remanufactured industrial equipment. The study provided insight into the present level of awareness and attitudes among the potential users. The results identified factors that influenced purchasing choices and helped in determining the acceptability of remanufactured products.

Respondents were from the manufacturing, technology, terminal operations, and energy sectors. The results indicated that a majority of the respondents had some familiarity with remanufactured equipment. About 75% of the respondents reported being "somewhat familiar" with the products of remanufactured equipment, while 25% were not familiar at all. None of the respondents had experience in buying remanufactured equipment, which suggested limited exposure and/or market presence of these products. Lack of familiarity is also highlighted in a comprehensive study by Parker et al. (2015), identifying it as the primary barrier and emphasizing the need for customer awareness of remanufactured products and their benefits. When asked if they would ever purchase remanufactured equipment, 87.5% responded they would consider it (Figure 8) and 12.5% answered that if the remanufactured product could meet the required performance criteria, they would switch from new to remanufactured.

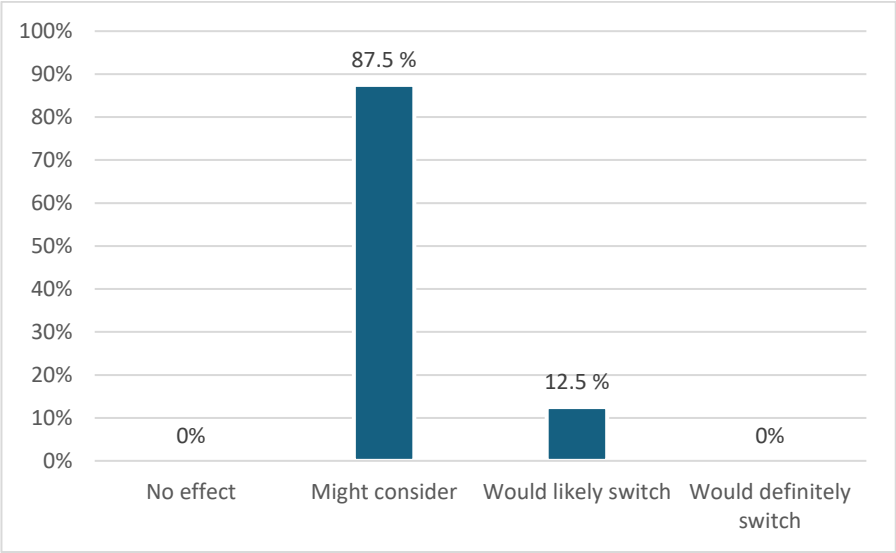

Figure 8 *Respondents' Consideration for Purchasing Remanufactured Equipment if They Meet the Industry Standards (Question. 4)*

However, when rating the likelihood of buying remanufactured equipment in the next procurement cycle, most of the respondents (62.5% in total, Figure 9) remained neutral. This suggested a small adoption of remanufactured products, with 12.5% explaining that they were likely to buy it, and the same number considered that it was either unlikely or very unlikely.

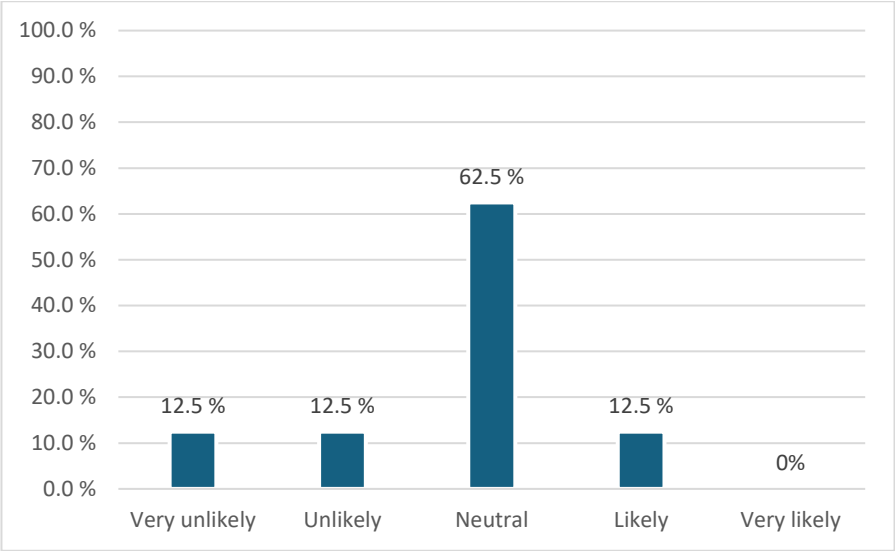

Figure 9 *Likelihood of Purchasing Remanufactured Equipment in the Next Procurement Cycle (Question. 5)*

When asked about the factors influencing their decisions to purchase remanufactured equipment, performance, and reliability were ranked as the most critical factors shown in Figure 10. This aligns with the study by Seitz & Peattie (2004) that also considered performance and reliability as key issues in shaping consumer perceptions of remanufactured products. Performance and reliability were followed by cost savings, with environmental impact ranking third as a key factor. Technological up-to-dateness and warranty and support services were placed lower in the ranking. Overall, these were predominantly economic and performance-related factors overriding sustainability in procurement decisions.

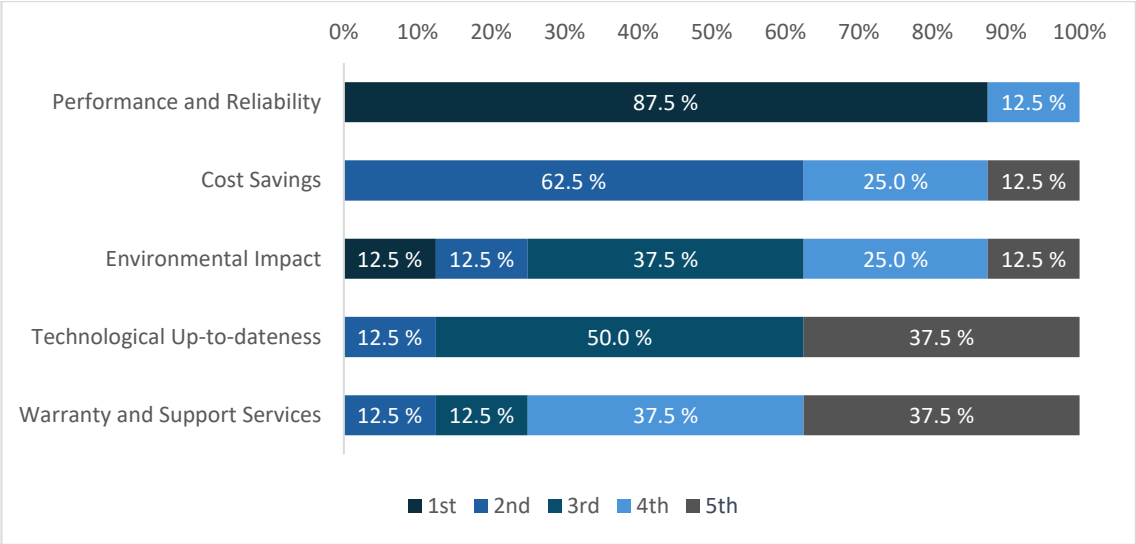

Figure 10 *Factors Influencing Decision to Purchase Remanufactured Equipment (Question. 6)*

Concerns related to remanufactured equipment focused on durability, lack of warranty, and performance consistency. For example, the majority ranked the long-term reliability of remanufactured products, and the absence of warranties highest shown in Figure 11, which suggested that those factors likely kept them from purchasing the remanufactured products instead of new ones. Respondents ranked performance consistency and technical support as the next highest concerns, while aesthetic imperfections were the least concerning.

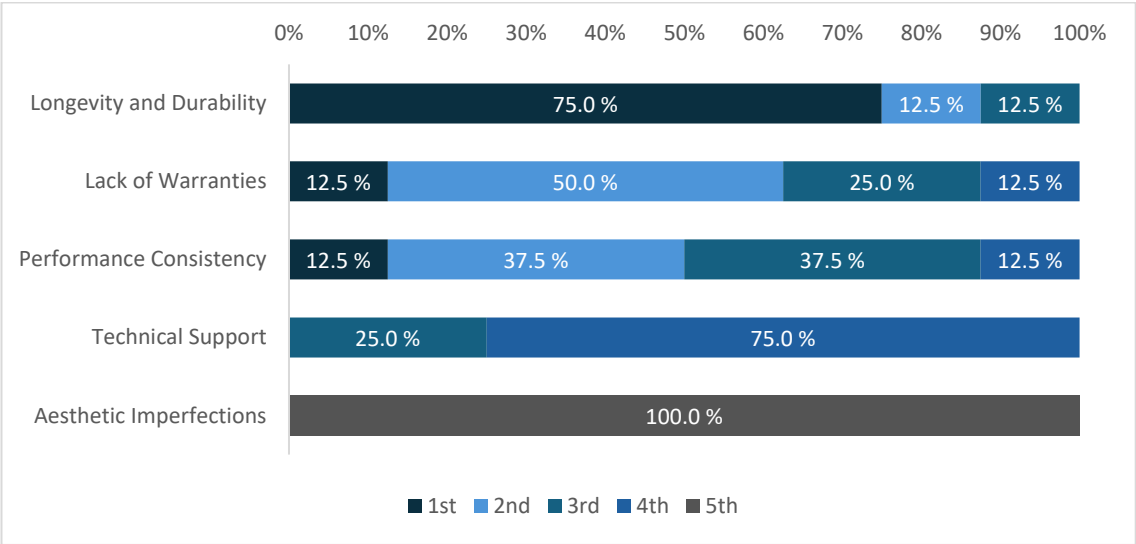

Figure 11 *Durability and Performance Consistency Concerns of Remanufactured Equipment (Question. 7)*

Respondents identified key barriers to purchasing remanufactured equipment as limited marketplace information, availability of suitable options, and higher costs compared to new products. These concerns were based on past experiences, particularly regarding durability and potential maintenance expenses. There were also concerns about remanufactured equipment costing more than new ones due to high labour costs. That in particular is not inexpensive to properly remanufacture, and this happens often in mining operations in Finland." Despite the barriers and concerns, there was interest in remanufactured equipment such as tanks, pumps, valves, reactors, and simpler, easily transferable equipment. However, some respondents remained undecided.

As far as the impact of a detailed study concerning successful remanufacturing practices is concerned, 50% of the respondents stated it would influence their next purchase decision. This highlighted the need for more comprehensive information to reduce certain concerns and to prove the economic and environmental benefits of remanufactured products. The remaining 50% were not sure, answering “maybe” which suggested that the acceptance of remanufactured equipment may well depend on the equipment’s performance, reliability, and how well they are documented and communicated. Accordingly, when asked about the importance of remanufactured equipment in supporting their company's sustainability goals, 75% of the respondents took a neutral view, while the rest stated that it was somewhat beneficial. This suggested that even though sustainability may not be a key driver in buying decisions, it was nonetheless seen as a potential benefit for remanufactured products.

In summary, the results from the survey showed that industry stakeholders are cautiously open to remanufactured equipment. The performance and reliability of the remanufactured equipment were crucial factors for the respondents, who indicated a moderate interest in exploring the options further. However, longevity, warranties, and lack of information were identified as important concerns that will have to be met if market acceptance is to be improved.

7. CONCLUSIONS AND RECOMMENDATIONS

This research compared the environmental and economic impacts of new and remanufactured SS chemical storage tanks through LCA and market analysis. It addressed sustainability concerns regarding remanufacturing practices with evident environmental and cost reductions. It also analysed market dynamics to determine how remanufactured equipment is perceived and identified key factors, such as performance, cost, and environmental benefits that influence its adoption. The research provided industries with comprehensive data to aid decision-making and promote sustainability.

The comparative analysis of new and remanufactured SS tanks highlighted several key findings. The environmental advantages of remanufacturing were well-evident. Results showed that the remanufactured tank required far less water (1 290 m^3 compared to 92 500 m^3) and consumed less energy (15 140 MJ compared to 66 317 MJ) than the new tank. Similarly, emissions emitted by remanufactured tanks were 95% less, which corresponds to a great reduction in environmental impact. These findings suggest that remanufacturing has the potential to be a greener alternative to conventional production, especially in terms of lower energy consumption and the depletion of natural resources.

The remanufactured tank was 32% more cost-effective compared to the new tank. The cost reduction was due to lower material, energy, and transport costs. Labour costs were also lower by 12%, contributing to the total cost reduction. Literature on remanufacturing supports this economic benefit, showing consistent cost savings in the 20-30% range, as discussed in Chapter 6.2. However, the study found that compliance costs were roughly 20% higher for remanufactured tanks due to the thorough testing required to meet the industry standards.

In terms of market analysis, the survey findings indicated a cautious yet open-minded attitude towards remanufactured equipment. The study observed a significant lack of awareness of the differentiation between remanufacturing and other processes, such as refurbishing or repairing. The lack of awareness was also observed that remanufactured products come with performance guarantees and are equivalent to new products. The misconceptions regarding low quality and reliability in remanufactured products have created a barrier to its adoption. Most respondents were neutral or uncertain whether they would consider remanufactured equipment in future procurement decisions. This suggests that more evidence on the benefits and performance guarantee of

remanufacturing is needed. There is great potential in addressing the concerns of durability, warranty, and perceptions of cost while providing more detailed information, which could enhance the acceptance of remanufactured equipment in the marketplace. This research faced certain challenges, including reliance on secondary data, limitations due to confidentiality constraints, and specific assumptions regarding data collection and analysis, all of which have been previously discussed. These challenges should be taken into account when interpreting the findings and considering directions for future research.

The findings from this study highlight the great potential of remanufacturing for improving industrial sustainability. It offers consulting companies the potential to play a bigger part in influencing environmentally friendly business practices. Consultancy companies can further enhance their services by offering remanufacturing as one of the most recommended solutions in industrial transformation. This will assist their clients in achieving their sustainability goals while reducing their environmental footprint. In particular, the enormous energy savings associated with remanufactured SS tank, along with the reduction in emissions and water use, indicate that remanufacturing can contribute to achieving SDG goals, and support the objectives of the EU's CE Action Plan. However, to maximize the potential of remanufactured products, more awareness of their benefits is needed. Policymakers and industries can use these insights to develop strategies and incentives to promote the adoption of remanufacturing, benefiting both the environment and the economy.

New technologies such as laser cladding, additive manufacturing, and advanced robotics could improve remanufacturing processes, making them more precise, reducing waste, and optimizing energy use. These advanced technologies may further reduce cost, and the time required for remanufacturing while increasing its adoption in various industries. Further research is needed to broaden the market analysis across industrial sectors, giving a more comprehensive view of remanufacturing adoption. These studies could be expanded to larger surveys, including nationwide efforts, to explore consumer and industry attitudes in more detail. Furthermore, additional research on the long-term performance and durability of remanufactured equipment could address concerns about reliability and warranties, improving market confidence in remanufactured products.

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APPENDIX A: SURVEY QUESTIONS

Questionnaire: Interest on the Purchase of Remanufactured Equipment

We are exploring interest in remanufactured equipment as a cost-effective and environmentally friendly alternative new equipment. Your responses will be used to develop our service offerings.

Thesis Author: Naheed Amiri-Moghal This master's thesis is conducted in collaboration with Rejlers Finland Oy and the University of Tampere. The topic is: Comparative analysis of environmental and economic impacts of new and remanufactured industrial equipment. Thesis Objectives: The main objective of the study is to compare the environmental and economic impacts of new and remanufactured industrial equipment through life cycle analysis and to explore market perspectives through a survey. For more information and contact: xxx@rejlers.fi

Responding to this survey is completely anonymous, and no personal information will be collected.

The survey will take approximately 2 minutes to complete.

Source of addresses: Rejlers Finland Oy customer database/CRM

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1. Which industry or type of business best describes your company?
   - Manufacturing
   - Healthcare
   - Construction
   - Automotive
   - Technology
   - Other (Please specify):

2. How familiar are you with the concept of remanufactured equipment?
   - Not familiar at all
   - Somewhat familiar
   - Very familiar
   - I have previously purchased remanufactured equipment

3. Does your company currently have a specific procurement target that could theoretically be considered remanufactured? If so, what is it?

(Open text field)

4. If remanufactured equipment could meet the exact performance standards required by new equipment, how would this influence your purchasing decision?
   - No influence
   - Might consider
   - Would likely switch from new to remanufactured
   - Definitely switch to remanufactured

5. Considering on your current procurement strategy, how likely would consider a remanufactured at the next procurement cycle?
   - Very unlikely
   - Unlikely
   - Neutral
   - Likely
   - Very likely

6. Rank the following in order of importance when considering purchasing remanufactured equipment, 1 being most important:
   - Cost savings
   - Environmental impact
   - Performance and reliability
   - Warranty and support services
   - Technological up-to-dateness

7. What are your concerns with remanufactured equipment? (1 being most concerning)
   - Longevity and durability
   - Performance consistency
   - Lack of warranties
   - Aesthetic imperfections
   - Technical support

8. What factors are currently preventing your company from purchasing remanufactured equipment? (e.g., lack of awareness of marketplaces, availability issues)

(Open text field)

9. Which category of remanufactured equipment are you interested in? (e.g., tanks, pumps, valves)

(Open text field)

10. Would a detailed study on successful remanufacturing practices influence your next purchase decision?
    - Yes
    - No
    - Maybe

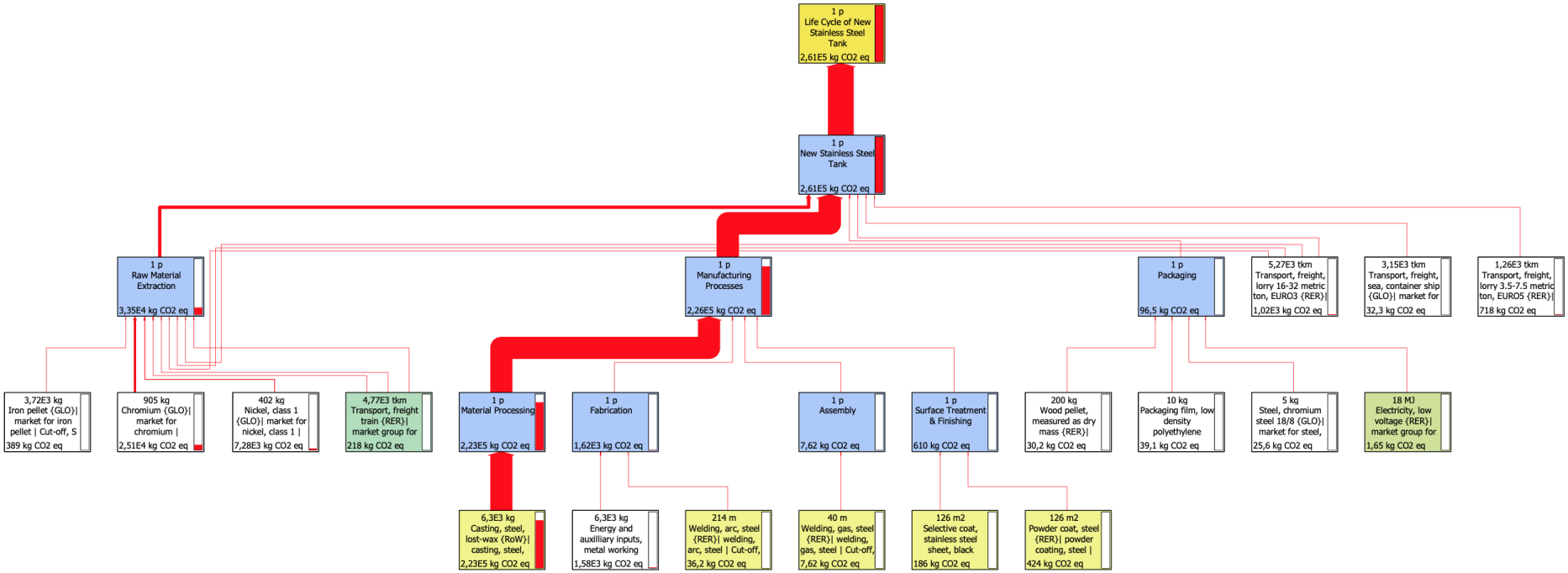
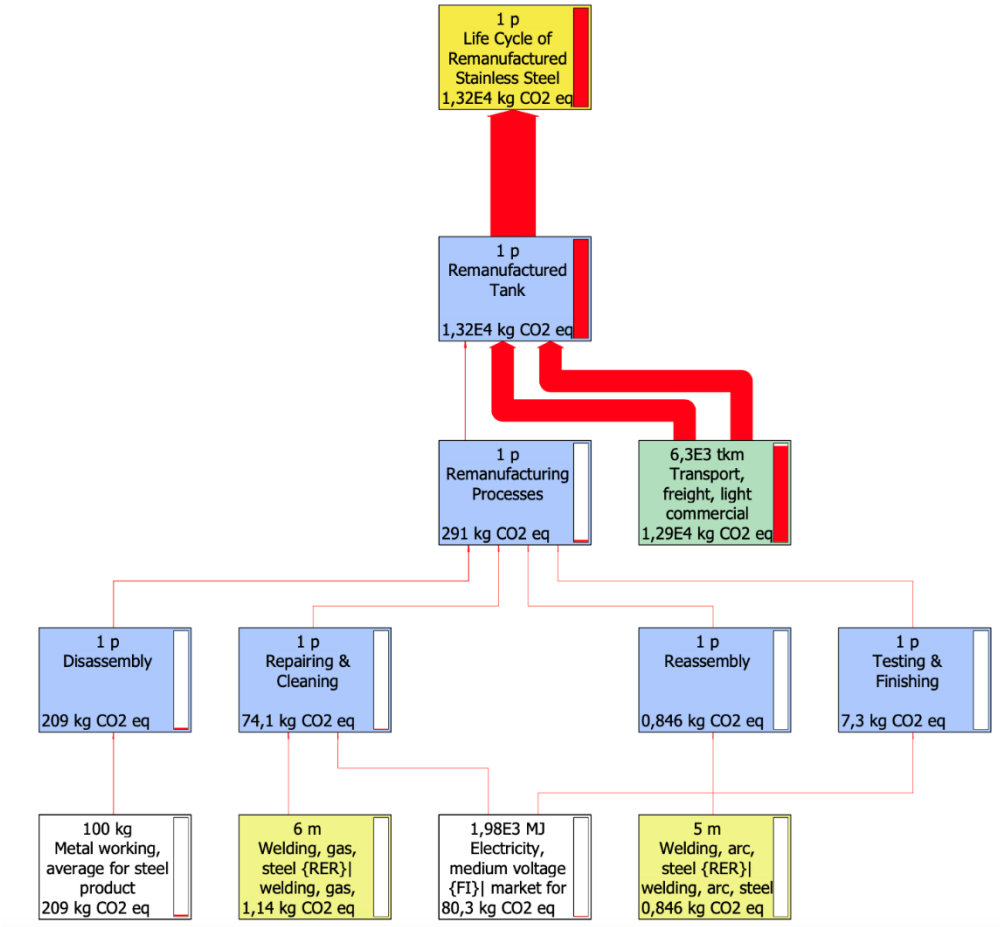
11. How important is the role of remanufactured equipment in supporting your company's sustainability goals?
    - Very beneficial
    - Somewhat beneficial
    - Neutral
    - Not beneficial

12. If you have any other thoughts or comments regarding remanufactured equipment, please write them here:

(Open text field)

We appreciate you taking time to fill out our questionnaire. Your input is very important to us, and it shall help shape our efforts in continuing sustainable and cost-effective solution offerings. We appreciate your feedback and look forward to serving you better.

APPENDIX B: NETWORK DIAGRAM OF NEW SS TANK



APPENDIX C: NETWORK DIAGRAM OF REMANUFACTURED SS TANK