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Remanufacturing and Refurbishment of Truck Spare Parts

A Mapping and Environmental Assessment
of Circular Processes

Master's thesis in Industrial Ecology

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SUMMARY

The transition towards a circular economy is considered important for reducing resource use and environmental impacts within the automotive industry. Remanufacturing and refurbishment are two circular strategies that extend the lifetime of components through a number of re-engineering processes. While this save materials, it is still important to evaluate the environmental impact from these activities.

The purpose of this thesis was to map circular process steps and component flows within remanufacturing and refurbishment of three truck spare parts at Volvo Group: a diesel particulate filter (DPF), an engine, and an electric vehicle battery. This was done through a semi-quantitative Material Flow Analysis (MFA). Additionally, the study aimed to assess the environmental impacts associated with the remanufacturing of the DPF and the engine through a Life Cycle Assessment (LCA). Hotspot and sensitivity analyses were conducted to identify key environmental impact drivers and evaluate the influence of transportation modelling assumptions.

The results of the semi-quantitative MFA showed that remanufacturing and refurbishment of components vary depending on the component characteristics. The LCA further showed that the environmental impact of remanufacturing is influenced by both component type and process complexity, with transportation and material replacement significantly affecting the results. These aspects should therefore be considered when assessing the environmental benefits of remanufacturing.

Keywords: Remanufacturing, refurbishment, automotive spare parts, Life cycle assessment, circular processes, battery, engine, diesel particulate filter, renovating

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Abbreviations

BEV – Battery Electric Vehicle

BMS – Battery Management System

CE – Circular Economy

CED – Cumulative Energy Demand

DPF – Diesel Particulate Filter

EF – Environmental Footprint

GHG –Greenhouse Gas

GWP – Global Warming Potential

ICE – Internal Combustion Engine

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LIB – Lithium-ion Battery

MFA – Material Flow Analysis

RME – Rapeseed Methyl Ester

SoH- State of Health

1. Introduction

This chapter treats the background, aim, and research questions of the study as well as scope, and general limitations.

1.1. Background

Since the industrial revolution, the amount of greenhouse gases in the atmosphere has increased drastically, and in 2024 the global average temperature was 1.55 °C above pre-industrial levels (European Commission, n.d.-a). A continued rise will give consequences such as extreme weathers, ice melting, sea rising, more droughts and extreme heat waves, meaning a serious impact on the environment, biodiversity, and human health (European Commission, 2024).

In response, the European Union has committed to climate targets within the Paris Agreement, aiming to limit global temperature increase to well below 2 °C and to pursue efforts to keep it below 1.5 °C. Under the European Green Deal and the European Climate Law, the EU has set a legally binding objective to achieve climate neutrality by 2050, alongside a target of reducing greenhouse gas emissions by at least 55% by 2030 compared with 1990 levels (European Commission, n.d.-b).

Meanwhile, global resource use continues to increase, and a similar trend is expected in the coming decades. Resource extraction could increase by as much as 60% by 2060 compared with 2020 levels and is linked to rising greenhouse gas emissions and other environmental pressures. (United Nations & International Resource Panel, 2024). At the same time, material demand, including critical and precious metals, is projected to grow in response to population growth, changing consumption patterns, and the increasing demand from infrastructure, services, and the clean energy transition. This, together with geopolitical challenges and vulnerable supply chains, means that a shift must happen to reduce overall resource use (United Nations & International Resource Panel, 2024).

The increased resource consumption is also connected to the linear economy, which is the current dominating economic system. In a linear economy, resources are mined, extracted, and refined into products that are disposed after use. This system is also called take-make-waste system (Kopnina & Poldner, 2021, pp. 1–3) causing depletion and landfill (Neves & Marques, 2022). An alternative economic system is the circular economy (CE), which aims to reduce waste by prolonging the usage of materials and resources (Ellen MacArthur Foundation, 2023).

In December 2025, the European Commission adopted the ReSourceEU Action plan, which focuses on securing EU's supply of critical raw materials, by securing supply chains, reducing dependencies from regions outside of Europe, and promote CE (European Commission, 2025). The Circular Economy Act, which is to be adopted by the European commission 2026, has a goal to create a market demand for secondary raw materials. As a part of EU's Clean Industrial Deal, the EU aims to increase the circularity rate, from 12% 2025 to 24% 2030 (European Commission, 2025a).

In the EU, the automotive industry is responsible for large volumes of material use. The industry consumes 10% of the European demand of plastic, and 19% of the steel, as well as a substantial share of copper, rubber, and glass. The shift towards battery electric vehicles (BEV) is further increasing material demand for copper and critical raw materials (Schwind & Reichert, 2024). In this context, large automotive manufacturers play a key role in shaping future material flows and decarbonization pathways. Additionally Geissdoerfer et al., (2017) highlight the importance of private businesses implementing circular strategies in the study *The Circular Economy - a New Sustainability paradigm?*.

One key actor in the automotive industry is Volvo Group. In 2024, the company had the largest share of the market for heavy trucks in Europe (Volvo Group, 2025a). Therefore, it can be considered an important actor when pushing for more circularity. Additionally, the company has a target of reaching net zero GHG emissions by 2040 (Volvo Group, 2025).

One important aspect of the heavy-duty automotive industry is the aftermarket (Saidani et al., 2018). It includes activities such as replacement, repair, and upgrading vehicle components

throughout their lifetime. Within the aftermarket, circular strategies such as remanufacturing and refurbishment can be applied to extend the lifetime of components. This includes partially reusing the material of a worn part, adding new material, and selling it as a spare part (Bobba et al., 2020). Remanufacturing a component includes restoring the product to the same or better condition compared to a new component, and it often includes the same warranty as one would get for a new component. Refurbishment of a component includes restoring the component to a performance that is as good as required for the component to work properly. It can, for example, mean that some parts are exchanged or repaired, or that the visual condition of the component is improved (Ellen MacArthur Foundation, 2021). Compared to the production of new components, these types of circular activities are expected to contribute to material savings and thereby contributing to overarching resource goals in the EU (Bobba et al., 2020).

A CE is seen as an important implementation to secure a sustainable future as it saves raw material and avoids landfill. However, it is also important to comprehend the implications of the full remanufacturing and refurbishment processes, and additional aspects of circular economies other than material savings to fully understand if it is environmentally beneficial (OECD, 2019). Therefore, it is important to investigate and understand the circular processes and their associated environmental impact.

Within Volvo Group, the circular remanufacturing and refurbishment of truck spare parts is characterized by an expertise of the site-based teams. However, there is a lack of centralized process documentation that can create barriers for supporting functions and colleagues at other locations. Hence, it is important to bridge the gap between operations and strategic analysis. Understanding the circular processes is also foundational to carry out environmental impact assessments.

1.2. Aim and Research Questions

The purpose of this master's thesis is to map circular process steps in the remanufacturing and refurbishment of three different truck spare parts: diesel particulate filter (DPF), engine

and electric truck battery. The mapping aims to provide documentation and an understanding of remanufacturing and refurbishment processes for these parts. This will be presented in a semi-quantitative Material Flow Analysis (MFA). In addition, the aim is to assess the environmental impacts associated with the circular processes of two of the selected components, the DPF and engine, through a Life Cycle Assessment (LCA), including associated transportation.

The LCA results will be further analyzed through hotspot and sensitivity analyses to identify key environmental impact drivers and potential areas for improvement within the selected circular systems.

To address the aim, the following research questions will be answered.

- What are the process steps and component flows within the remanufacturing and refurbishment of the DPF, engine and electric vehicle battery?
- What are the environmental impacts associated with the remanufacturing and refurbishment of the DPF and the engine?
- What are the hotspots in the circular processes of the two environmentally assessed components, and how do specific process steps compare in terms of their environmental contribution?
- How sensitive are the Climate Change impact results to assumptions regarding transportation?

1.3. Scope

The scope of the study is presented below.

1.3.1 Geography and Time Frame

The scope of the study is limited to the internal remanufacturing and refurbishment business by Volvo Group, and does not consider the externally remanufactured and refurbished components that Volvo Group purchases. The internal remanufacturing and refurbishment in this study is limited to European renovator sites in Sweden and in France. The data collection

is primarily concentrated in Europe. However, as the Volvo Groups business is global, the geographical scope of the study will be global including transport from across the world. The data collected will primarily be from 2025, with exceptions when the data availability is limited.

1.3.2 Component Selection

This study includes three selected truck spare parts used within Volvo Group’s internal remanufacturing and refurbishment operations. The components were selected following an initial investigation of the remanufacturing and refurbishment within the company. The components were selected because they represent different types of truck spare parts and involve varying remanufacturing and refurbishment processes. This variation allows the study to capture a broader understanding of different circular process steps.

The included components, together with renovator site location, are presented in Table 1 below.

Table 1 Selected components and renovator sites

Component	Renovator site	Circular method
Engine	Sweden	Remanufacturing
Diesel particulate filter	France	Remanufacturing
Battery	Sweden	Refurbishment

The study focuses on heavy-duty truck components, and internal component variants are not distinguished. Each component is therefore modelled as a generalized category (e.g., “engine”), representing typical configurations within the remanufacturing and refurbishment business.

The engine and diesel particulate filter are components associated with internal combustion engine (ICE) trucks, while the battery is a BEV component.

1.3.3 Motivation of Methods

The study consists of both a semi-quantitative Material Flow Analysis and a Life Cycle Assessment. The semi-quantitative MFA includes all three selected components and aims to map, document, and get an understanding of the process steps involved in the circular processes and the component flows. The LCA is conducted for two of the three components to assess the environmental impacts associated with the circular processes and related transportation. The environmental impact will be calculated for the engine and for the DPF.

Due to limitations in available data, the battery is not included in the environmental assessment.

1.4. Limitations

The number of remanufactured or refurbished spare parts considered in this report is limited to the list presented in Table 1. While they represent a share of the internal remanufacturing and refurbishment business within Volvo Group, they do not capture the full diversity of circular process steps within the business. However, as mentioned above, they were chosen because the components were considered to have varying characteristics and to be important either currently or in the future.

One focus of this study is to assess the environmental impacts associated with the remanufacturing and refurbishment of the two selected components, the DPF and the engine. However, these results are not compared to those of new spare parts. Although there are some environmental impacts for new components available, the LCA conducted in this study are performed at a more detailed level, making a direct comparison inconsistent and potentially misleading.

Furthermore, due to the scope of the study, a full LCA of the corresponding new components will not be conducted. While such a comparison could provide additional insights into the relative environmental performance of remanufactured components, it is outside the scope of this thesis.

The selected components represent different types of products and circular processes. One limitation of the study is that the environmental impacts of the circular processes were only assessed for the DPF and the engine, and not for the battery. The exclusion of the battery from the LCA limits the possibility of gaining a broader understanding of environmental impacts can vary across different component types.

2. Theory

The following section will be a theoretical background of central concepts within the study.

2.1. Circular Economy

Circular economy aims to reduce resource extraction by having a closed loop for the materials. At the end of a use phase materials are seen as a resource rather than waste, and the goal is to maintain a high utility and value of the material (Geissdoerfer et al., 2017). The design of products should aim to “slowing, closing and narrowing resource loops” (Bocken et al., 2016). In accordance with the Brundtland definition of sustainability, considering both current and future generations, a circular economy aims to assure available resources for both currently and for the future (Bocken, 2024).

When the flow of resources avoids the waste stage, the lifecycle continues. The resource lifecycle can then be called cradle to cradle. The material is extracted from its cradle, used during the usage phase, and is then used as a resource again, returning to the cradle phase (Ratten, 2024). This creates a waste free economic system that decouples economic growth and resource extraction (Ghisellini et al., 2016).

There are several circular strategies that can be used to prolong the life of a resource. An overview of strategies can be seen in Figure 1 below called the 9Rs. The strategies included are refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover. Refuse is the first step, which avoids extracting any resources at all. The next activity is Rethink, which includes increasing product utilization by, for example, promoting sharing products. Reduce means increasing resource efficiency during product production and use, so less material is used for the same function. Repair includes fixing faulty parts so that the product can function again. R5 and R6 is refurbishment and remanufacture, which has red squares in Figure 1. Refurbishment refreshes a component so that it can be used again, while remanufacturing restores it into its original performance. A more detailed description of remanufacturing and refurbishment is included in 2.1.2 and 2.2.2. R7 is repurpose, where the used product is used again but with another purpose. Recycle includes

processing materials into its basic materials or substances and reprocess them into new materials. Recover can be an incineration to recover energy from the material (Muñoz et al. 2024).

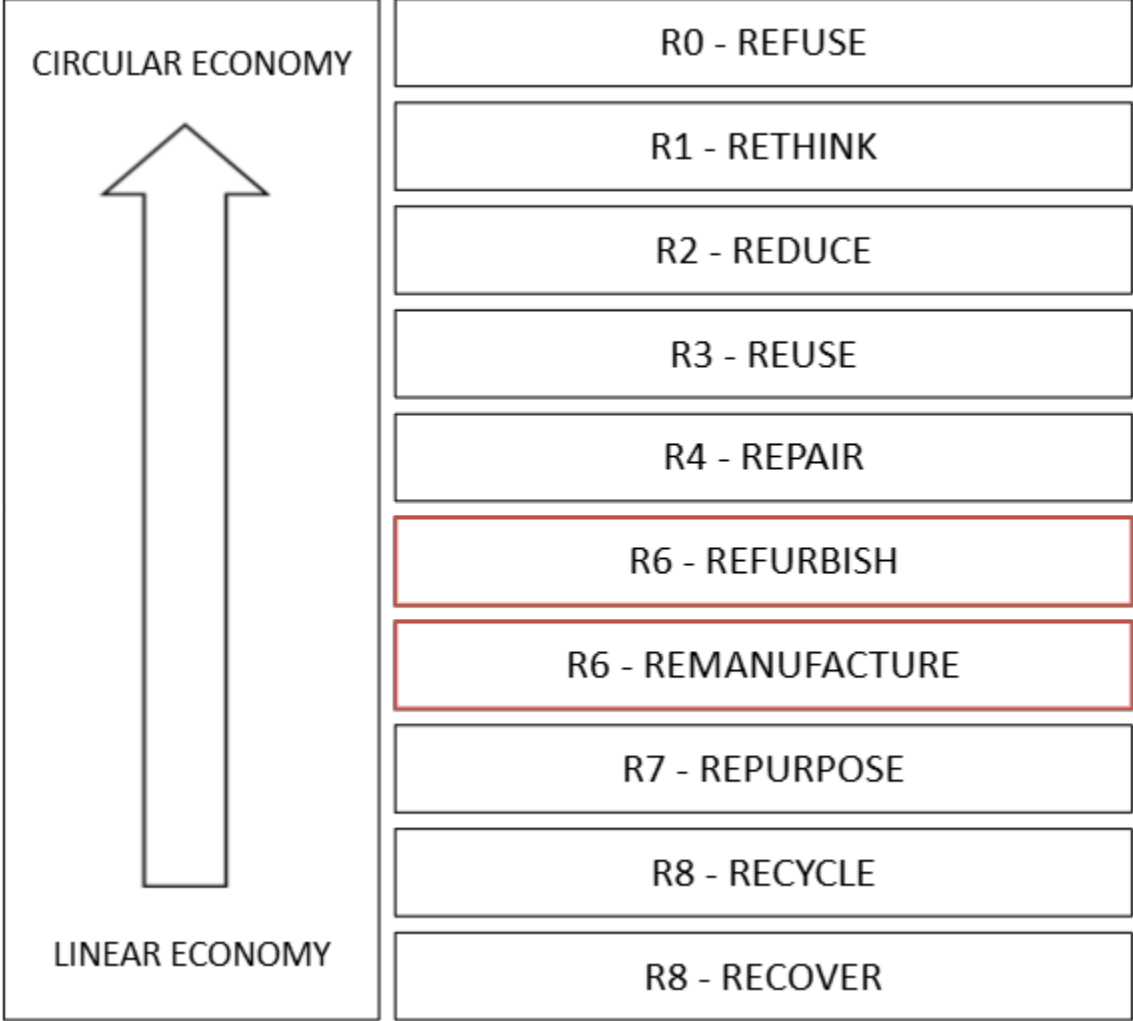


Figure 1. Overview of the R-framework

2.1.1 Circular Business within Volvo Group

Within Volvo Group’s business, the aftermarket is of importance. The aftermarket consists of services provided after the initial sale of the truck, including maintenance, repair, as well as the supply and exchange of spare parts throughout the vehicle’s operational lifetime. It is

within these aftermarket activities that the remanufacturing and refurbishment of components takes place (Volvo Group employee, personal communication).

2.1.1.1. *Remanufacturing*

When a product is remanufactured, it is disassembled and restored using previously used parts from the original product, combined with new materials. The old, used component that is being restored is called *core*. The remanufacturing brings the component back to a condition as good as new. The core is disassembled to a level of optimal depth (Kampker et al., 2020). The remanufacturing process takes place in a factory and should bring the product back to at least the same performance capabilities as when it was new (Russell & Nasr, 2022).

To take the product back into as good as new condition, there are several common steps within remanufacturing. These are for example, disassembly, inspection, cleaning, part replacement, and reassembling (Sundin, 2004). What each step consists of, for example, what kind of cleaning method that is used, varies between products.

Remanufacturing within Volvo Group

Remanufactured components within Volvo Group must meet the criteria of being “as good as new”, meaning that their functional performance, reliability, and durability are equivalent to those of corresponding new components. As a result, remanufactured components are offered with the same warranty as new spare parts (Volvo Group employee, personal communication).

Volvo Group has a centralized remanufacturing system in Europe, meaning that all renovations happen in a limited number of renovator sites and storage facilities. To provide an understanding of the remanufacturing business within Volvo Group, a flowchart is presented in Figure 2, followed by a descriptive text below.

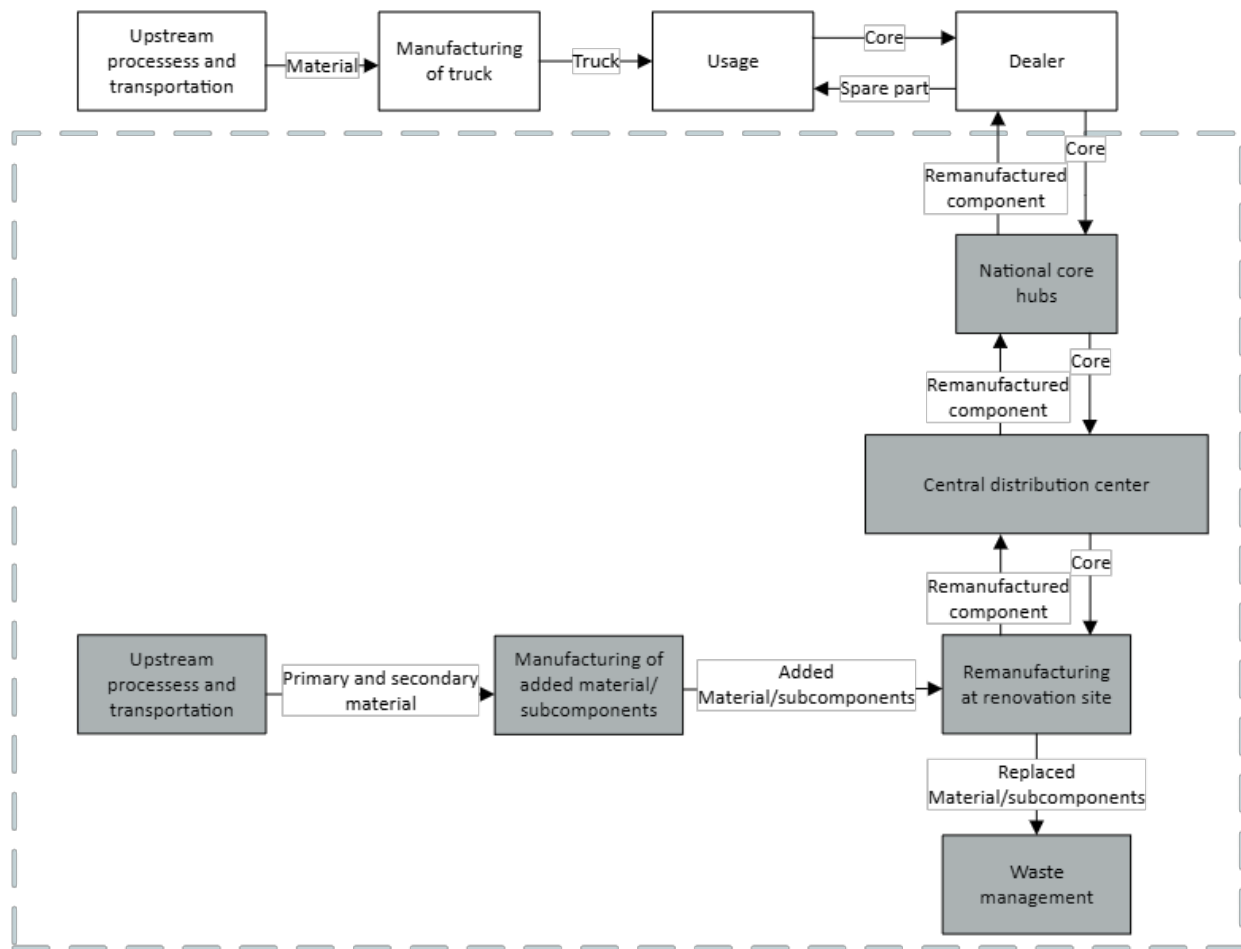


Figure 2. Flowchart of remanufacturing logistics and the component flows

At the top of the figure, the first lifecycle of the truck is visible, including manufacturing of the truck with associated upstream processes, and usage of the truck.

When a component in the truck needs to be exchanged, the truck owner can approach a dealer who provides a spare part. The core is given to the dealer. The dealer sends the core via core hubs distributed across regions, to the central distribution center, located in central Europe. The core is thereafter sent to the renovator site.

At the renovator site, the component is remanufactured. The remanufacturing includes a number of process steps, as mentioned before. In addition to this, subcomponents or specific parts might need to be replaced for the specific component being remanufactured. This can for example be if subcomponents are worn out and cannot be repaired. These subcomponents

are replaced with new ones. As the core is received at the renovator site has varying quality, the amounts of subcomponents that must be replaced can vary largely. The added material and/or subcomponents have upstream processes, and the replaced material and/or subcomponents go to waste management.

The colored boxes enclosed by the dashed line represent the activities most closely associated with remanufacturing and are therefore in focus in this study.

2.1.1.2. Refurbishment

Refurbish is higher ranked than remanufacturing in the hierarchy of the 9Rs, which means that larger parts of the material are salvaged. Refurbishing brings the product back to its intended function. The functionality standards are not necessarily as good as new, but the product must be fully functioning. The modification of a product in refurbishment is smaller than the one in remanufacturing (Russell & Nasr, 2022). While remanufacturing usually includes replacing parts and materials, refurbishing is more focused on testing and restoring the product's functional condition (Ellen MacArthur Foundation, 2019).

Refurbishment within Volvo Group

Refurbished spare parts within Volvo Group can be defined as being “as good as required”. The warranty is not the same as buying a genuine spare part, since the product is not expected to have the same lifetime as a new part. Within Volvo Group, the refurbishment business is not as large as the remanufacturing business, and is mostly focusing on batteries, as they are difficult to meet the requirement of remanufacturing, which is “as good as new” (Volvo Group employee, personal communication).

The refurbishment business follows the same logistics as the remanufacturing business. Therefore, the flowchart in Figure 2 is also applicable to refurbishment.

2.2. Previous Studies and Literature

There is a lot of literature available on circular strategies as a way to mitigate environmental impacts. The studies focus on a broad range of products and circular strategies. While the number of papers and studies focusing on circularity, remanufacturing receives a lot more

attention than refurbishment. Additionally, LCA is a common method used in the literature, while a semi-quantitative MFA in the same context as in this study has not been encountered.

As mentioned, LCA is a methodology commonly used to assess environmental impacts. However, in contrast to this study, the literature mainly uses the LCA to compare the environmental impacts for a new produced component and a remanufactured component. Several of the components in the intended scope of this study have previously been subject to LCA studies. A meta-analysis done by Peng et al. investigated a range of products, including engines, engine gearboxes, transmissions, and compressors. The study compared remanufactured and new mechanical components, which showed that remanufacturing can reduce GWP by over 50% if the use phase and end of life phase is excluded (Peng et al., 2022).

In general, remanufacturing has a low energy demand as the remanufacturing activities often include manual labor such as disassembling or inspecting the product (OECD, 2019). Remanufacturing can save up to 80 % of energy use, but as the remanufacturing process can differ, as well as use of new resources, the actual environmental benefit varies (Ellen MacArthur Foundation, 2016).

The result of the environmental impact of remanufacturing also depends on the remanufacturing method. Zheng et al. performed an LCA on a heavy-duty diesel truck engine, and compared a new manufactured engine, with engines remanufactured with traditional remanufacturing techniques and with more advanced remanufacturing techniques. In traditional remanufacturing processes, damage on components surface because of corrosion or wear is repaired with machining techniques. However, sometimes components cannot be recovered with traditional machining, for example if a component has very fine cracks, and the component will in those cases be discarded. Advanced remanufacturing techniques examined in the study by Zheng et al (2019). are laser cladding, arc spraying, and brush electroplating. The results of the study showed that remanufacturing with advanced restoring techniques had lower environmental impact in 6 out of 7 impact categories compared to the traditional technique, while water use was higher for the advanced

technique. In both remanufacturing scenarios, large impacts come from producing new replacement components, not from the restoring operations. This means that increasing component reuse is an effective way to reduce impact (Zheng et al. 2019).

Yoshimura et al. (2024) conducted an LCA of diesel particulate filters (DPFs) used in construction machinery and found that environmental impacts are driven by raw material production and manufacturing of new filters. By replacing one new DPF with a remanufactured unit, reductions of approximately 47% in global warming potential and 50% in resource consumption were achieved. The authors argue that the material production of especially ceramics, which for some DPFs can be a large part of the mass, and platinum group metals, which act as catalysts for exhaust purification, accounts for much of the impact. At the same time, the transport and remanufacturing, transport and disposal of a used product had a lower impact (Yoshimura et al. 2024).

In another study, by Koroma et al (2022), the refurbishment of Lithium-ion battery (LIB) has been assessed as part of an LCA of a full BEV. Refurbishment is used more extensively on batteries, rather than remanufacturing. This is partly due to the construction of the batteries, which makes it difficult to reach the required depth of the disassembly which is needed for a reman process (Kampker et al., 2020; Neri et al., 2024). The refurbishment process includes battery collection, disassembly, battery State of health (SoH) testing, and refurbishment. The SoH testing decides if the battery is suitable for refurbishment. According to the study, the end of life of a LIB is reached when the state of health of the battery is between 70-80% of initial quality. The battery cell will not always pass the inspection stages. The rate at which the cells are assumed to pass the initial quality assessments varies. While the study by Koroma et al. used a core conversion rate at 50%, the authors also concluded that the rate varies between 10-100% in other studies (Koroma et al., 2022).

Apart from the common steps in the remanufacturing process mentioned before, there are other aspects to remanufacturing that can contribute to an increased environmental impact, such as transportation (OECD, 2019). In a linear supply chain, the transportation of resources

and products follows a planned route. When remanufacturing products, the core must be collected, which can possibly add long distances of transportation (Ullah, 2023).

3. Method

The methodology of this study consisted of a semi-quantitative MFA, an LCA, and associated data collection. The data collection was done by literature review, document collection, interviews and study visits. Initially, the method of the semi-quantitative MFA is presented, followed by the LCA methodology. As the data collection for both the semi-quantitative MFA and the LCA relied on the same methods, the chapters for the literature review, document collection, and interviews apply for both the semi-quantitative MFA and the LCA.

3.1. Semi-Quantitative MFA

To map the remanufacturing and refurbishment processes we have introduced an adaption of an MFA that in this study has been named semi-quantitative MFA. It hence builds upon the methodology for an MFA, which studies the flow of material in a defined system. An MFA shows and quantifies the sources, flow, and sinks of the material under study. It follows the principles of conservation of mass, and therefore can be used to track resource origin, processing, how long resources stay in use, and where they end up. An MFA can give information about all flows and stocks of a material and show the sources of waste and environmental loading. In this semi-quantitative MFA, all material flows are not quantified, and the adaption is described below.

An MFA is an iterative process that consists of a number of steps explained in section 3.1.1-3.1.5.

3.1.1 Adaptation of the MFA Approach

In this study, the MFA methodology is applied in a modified and semi-quantitative form. While the general MFA framework by Brunner & Rechberger (2004) presented in this section is followed, the focus is not on detailed substance-level mass flows. Instead, the MFA is adapted to the context of this study, which is to map the remanufacturing and refurbishment. The purpose of this adaptation is also to support the life cycle inventory (LCI)

development by identifying relevant processes and material flows rather than providing a complete and fully quantified mass balance of all substances.

The purpose of the semi-quantitative MFA is also to map components or subcomponents leaving and entering the system, and if relevant, assess the material efficiency and material losses in the system. As a result, the MFA in this study is primarily conceptual and descriptive, with quantification applied only where data is available and where it is relevant for understanding key component flows. Flows that are not quantified are still included qualitatively.

3.1.2 Problem Definition

The first step of conducting an MFA is problem definition. In this step, the problem is defined, and the goal of the MFA is decided.

3.1.3 System Definition

The second step in the MFA is the system definition, where the system boundaries are defined and the selection of substances, goods and processes are made with regards to the goal of conducting the MFA (Brunner & Rechberger, 2004).

The system boundary is defined in both time and space. The chosen system should include all necessary processes and material flows and avoid inconsistencies or become larger than necessary. The spatial boundary decides where system is being studied, and may, for example, be defined as a nation, region, or city. The temporal boundary specifies the time period over which the system is studied, typically as a snapshot of a specific year, preferably using the most recent data available.

In a traditional MFA, the selection of relevant substances and goods is carried out at this stage (Brunner & Rechberger, 2004). In this semi-quantitative MFA, this step is adapted to instead focus on the selection of relevant components and subcomponents within the remanufacturing system.

The determination of relevant processes is also made, where processes can be transport, transformation, or storage of materials. The resulting flowchart should not be too complex or

too simple, and the selected processes can be aggregated to simplify the flowchart or divided into smaller subprocesses to provide a more detailed representation (Brunner & Rechberger, 2004).

3.1.4 Determination of Mass Flows

After the system has been defined, determination of mass flows is done. This includes data collection through, for example, databases, literature, interviews, measurements, or scientific papers (Brunner & Rechberger, 2004). In this semi-quantitative MFA, this step includes identifying and describing the movement of components through the remanufacturing and refurbishment processes, and quantifying flows where it is relevant and where reliable data is available.

3.1.5 Illustration and Interpretation

The results of the MFA should be presented so that the relevant findings are clear, understandable, and trustworthy. The results can be illustrated through a flowchart showing all stocks, material flows, and flows entering and leaving the system. All elements in the flowchart should be clearly named and quantified. Although as mentioned, in this semi-quantitative MFA, there are flows that are only included qualitatively. The results should also be interpreted, and the implications of the findings should be discussed (Brunner & Rechberger, 2004). In this study however, the implications and discussion of the results of the MFA are limited, as it is mostly used as a tool to understand the remanufacturing processes and support the LCI.

3.2. LCA

LCA is a tool used to assess the environmental impact of a system or product throughout its lifecycle. The full lifecycle starts at the cradle with raw material extraction, and ends with disposal at the end of life, called the grave. The LCA study considers all stages in between, such as production and usage (Baumann & Tillman, 2004).

To ensure harmonized performances of climate impact calculations using LCA, there is a standardization called the ISO 14040 and 14044 standard (ISO, 2006). The standards guide

planning and execution of LCA studies. Meanwhile, Volvo Group also has internal documents that guide their internally conducted LCAs further to ensure consistent and comparable results.

An LCA is carried out in four iterative steps, which are described in the following subchapters. The iterative workflow procedure is visualized in Figure 3 (Baumann & Tillman, 2004).

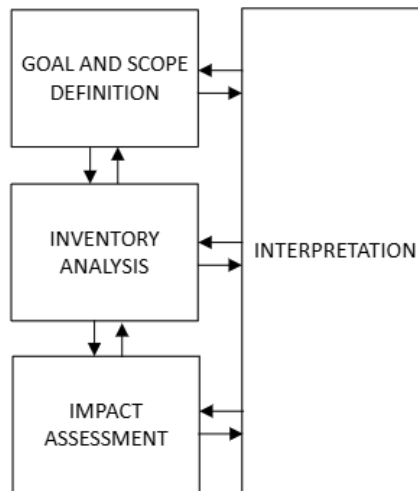


Figure 3. Illustration of the iterative workflow of executing an LCA

3.2.1 Goal and Scope Definition

The first step is the goal and scope definition, where the intended use of the study is introduced. It includes what the product of the study is, why the study is done, and who it will be communicated to. The functional unit is introduced, which gives a quantification of the function of the system, and acts as a quantitative reference that all inputs and outputs of the system are normalized to. This ensures that the results are comparable (Baumann & Tillmann, 2004). System boundaries are also introduced here, as well as the considered environmental impacts (Baumann & Tillman, 2004).

3.2.2 Inventory Analysis

The goal and scope definition is followed by the inventory analysis where a model of the life cycle is created based on the conditions from the goal and scope definition. Data is collected on all input and output flows between processes, including their respective quantities.

Thereafter, calculations are made of resource use and the concerned emissions (Baumann & Tillman, 2004).

3.2.3 Impact Assessment

The third step is the impact assessment, where the environmental impact of the inventory data from the previous step is calculated. This is done through applying characterization factors for the chosen impact categories, which describes its contribution to specific environmental impacts (Baumann & Tillman, 2004).

3.2.4 Interpretation of Results

The fourth step in the LCA is the interpretation, where analyses and conclusions are being drawn and communicated to the intended audience (Baumann & Tillman, 2004).

3.3. Data Collection

The data collection was carried out through literature review, document collection, interviews, and study visits. The four data collection methods were used iteratively and adaptively, since the scope of the remanufacturing and refurbishment process mapping was complex and not fully defined in advance.

Site-specific knowledge from interviews, internal documentation, and information from study visits was prioritized, particularly for understanding the remanufacturing and refurbishment processes, since these sources were deemed to have the most updated information of actual processes. All interviews, study visits and most document collection was conducted within Volvo Group focusing on internal data and understandings.

3.3.1 Component Modelling and Representation

Each component in this study is represented as a generalized component rather than distinguishing between individual product variants. For example, the component “engine” includes multiple heavy-duty truck engine variants. Both 17-litre and 13-litre engines are manufactured, and within those categories the engines vary in terms of power and torque (Volvo Group, 2026d). In this analysis, they are presented as a single aggregated component.

However, the data collection for the heavy-duty truck engine primarily focused on the engine model that is most commonly remanufactured, and it is considered representative for the engine category. The data collection for the diesel particulate filter focused on a heavy-duty truck DPF that was considered the representative. Similarly, the battery data collection focused on one battery variant, which accounts for the largest share of Volvo Group’s internal circular battery business. Where specific data for individual components were not available, averages across similar components were used.

3.3.2 Literature Review

A literature review is a critical research methodology to give an overview of a specific field, and it can validate the motives of the study and help frame the aim (Snyder, 2019). In this study, the literature review was conducted to understand the current knowledge gaps and to create a foundational understanding of the area. It was also used when the primary data was uncertain. Then literature was used to compare the retrieved data with values presented in similar studies.

The remanufacturing and refurbishment operations in found studies were often very case-specific and not directly comparable to the internal processes considered in this study. Therefore, the literature was not used for identifying component flows or process steps within Volvo. It was however used to confirm whether identified circular process steps are commonly occurring in remanufacturing and refurbishment of similar components, and to enable comparison with findings from other studies.

The literature review was done by using several databases, such as Google Scholar, ScienceDirect, and Scopus. Key search terms that were related to the aim and research questions of the study were used, such as “Material flow analysis”, “Life cycle assessment”, “Remanufacturing”, “Refurbishment”, “Automotive industry”, “Heavy-duty vehicles”, and more specific truck components such as “Engine”, “Battery” and “DPF”. These key words were used in different combinations.

3.3.3 Document Collection

Document collection was a part of the method (Blomkvist & Hallin, 2014, p. 69). This applies to internal documentation within Volvo Group, which was primarily used to get an early understanding of the remanufacturing and refurbishment processes as well as for data collection. For the semi-quantitative MFA, Technical Requirements Documents were the primary documents used to support the study. These documents regulate the quality and safety standards of the production and ensure that the remanufacturing and refurbishment follows the set standardization. The information gathered and used from internal documents was cross-checked and validated through interviews to reduce the risk of relying on outdated data.

Likewise, the LCA study relied on internal documentation. This included for example data obtained from measurements on machines, production volumes for renovator sites, transportation volumes from different countries, purchasing data for the renovator site, and data regarding which subcomponents were replaced and how frequently replacements occurred.

3.3.4 Interviews

Interviews were conducted with employees at Volvo Group. Interviews were chosen as it made it possible to retrieve data that were not documented, collect expertise knowledge while having the flexibility allowing for clarifications and adjusting the focus depending on the answers from the participant (Hammond & Wellington, 2020).

Different types of interviews were done through different stages of the project, and in total 50-60 interviews were conducted. The interviews used various types of semi-structured approaches, meaning that predefined questions guided the discussions, while additional follow-up questions were asked depending on the expertise of the interviewee and the direction of the conversation. The interview approach varied depending on the information previously known about the interviewee and the specific objectives of the interview.

As mentioned, the data collection process was iterative and adaptive. Meetings were therefore scheduled when new data gaps were identified, depending on what information that had been collected, rather than following a predefined interview plan. In many cases, follow-up interviews were conducted with the same interviewees when additional clarification or more detailed data were needed, or when the interviewees had gathered requested information relevant to the study.

Initially, explorative interviews were used, which can be helpful to build understanding of a topic and identify knowledge gaps (Panke, 2018). They were used to gain an understanding of Volvo's circular strategies, identifying key components within remanufacturing, as well as identifying main process flows. The early interviews also focused on understanding what documentation already existed regarding the remanufacturing process steps. Hence, it also supported the document collection. The interviews also aimed to find new internal contacts that could have knowledge about the detailed data needed.

At a later stage, the focus of the interviews shifted more towards mapping the remanufacturing and refurbishment processes for different components and quantifying flows for the LCA. To map the full remanufacturing processes, semi-structured expert interviews were used with a prepared set of initial questions that were followed up with new ones as the understanding of the topic developed during the interview (Hammond & Wellington, 2020).

The collection of more detailed data that occurred after the mapping was done had a more structured approach. However, the interview methodology would still be considered semi-structured. Since the interviews were conducted with experts working in different areas and

focused on different data collection, each set of prepared questions differed. That is, the same set of questions were not used for several interviews (N. Phellas et al., 2012)

All interviews were conducted in person or via Microsoft Teams. Given that this study is technical and quantitative, the information from the meetings was documented by extensive note taking and, if applicable, by directly entering data into data collection sheets or into the mapped flow chart structure of the remanufacturing and refurbishment process.

The interviews were conducted in pairs, meaning there were always two interviewers. One interviewer was responsible for leading the meeting while also taking notes. The other interviewer supported by asking follow-up questions and ensuring consistent documentation of information. If any information was unclear, unheard, or missed, the interviewee was asked to repeat or clarify.

The purpose of the interviews was not to capture qualitative narratives or to conduct interpretative analysis of interview content. Therefore, real-time documentation in notes and data collection sheets was considered the most appropriate method. This documentation approach was also chosen for practical reasons, as it was clear in the beginning of the project that many interviews would be conducted in an iterative and explorative process. Recoding and transcription were therefore considered impractical given the volume of interviews and the purpose of the interviews. In addition, most interviews focused on straightforward process data, which could be reliably captured through note taking and by directly entering the data into data collection sheets. When a larger amount of data was retrieved, this was sent via email or teams to avoid any mistakes in the data collection.

Immediately after each interview, the notes were reviewed, discussed, and summarized to ensure that no information was lost. This step also helped to validate the data and to identify progress and data gaps during the data collection process.

3.4. Study Visits

As a part of the data collection, study visits were made to two renovator sites in Sweden. The purpose of the study visits was to collect data on site and to get a better understanding of the remanufacturing process.

The study visit to the first renovator site was conducted to get a better understanding of the remanufacturing process of the engine. The visit was also used to collect data from operators working on-site with the components, as they were deemed to have the most updated information. The purpose was to understand and collect data for the machines used in the remanufacturing process. This could either be to check the brand and model of the machine or collect data from the rating plate of the machine, that showed electricity and voltage at max effect. Furthermore, an understanding of, for example, auxiliary material use and material exchange was collected. Operators on the site also estimated time consumption for the machines, to be used together with electricity data. The study visit was documented by taking notes and pictures. The study visit was prepared by documenting the remanufacturing process of the engine as detailed as possible beforehand, to then check if the information was correct on site. It was also prepared by detailing what kind of information was needed to the guide at the site.

The study visit to the other renovator site focused mainly on measuring the electricity consumption of machines in use and compare it to the top effect of the machines, stated on the rating plates. This was done together with colleagues at Volvo Group. The electricity was measured on two washing machines at different times, and this was used to calculate a factor, here called Utilization factor. This factor was used together with the top effect from rating plates to estimate the actual electricity being consumed by the washing machines in the first renovator site. This method was used since the actual electricity consumption of the washing machines was not known. However, this method also introduces uncertainties to the result and may overestimate or underestimate the actual electricity consumption. The information from the study visit to the second renovator site was documented by note-taking and pictures.

3.5. Methodological Limitations

Several limitations are associated with the applied methodology. The semi-quantitative nature of the MFA means that the study does not provide a fully detailed mass-balance of all material and energy flows. Instead, the semi-quantitative MFA aims to map selected component flows and process steps. Some flows are therefore treated only qualitatively, and flows of smaller components are excluded entirely. As some smaller components are not mapped, this simplification impacts the representation of the result. However, the selection of components included is made through guidance from on-site experts.

If these smaller components have their unique remanufacturing process steps, the process step is excluded from the LCA. These unique remanufacturing processes are however expected to have a very small relative impact on the environmental load (Volvo Group employee, personal communication).

The study partly relies on expert knowledge, estimations, and interpretations. Interview responses may vary between experts, and process understanding depends on communication and individual experience. Furthermore, internal documentation was not always fully up to date and therefore required validation through expert interviews. As a result, the findings represent the best available understanding based on the data sources accessible within the study.

As mentioned, all three components included in the study exist in several variants. The data collection focused on a specific, yet representative, engine model, a representative heavy-duty truck DPF, and a specific battery variant. The results are primarily based on these specific variants but presented at component level. Although these were selected as representative, variations in circular processes and environmental impacts between different variants are not captured in this study.

4. Component Description

In this section, the included components of the study are introduced. Firstly, the DPF is introduced, followed by the engine, and finally the battery.

4.1. Component Description - DPF

DPFs are used to remove soot and emissions from the exhaust gases in vehicles (Johansson, 2022). It has an approximate weight of 10-20 kg and reduces hazardous emissions and particulate matter from burning diesel, which is important to follow environmental guidelines and regulations. As it is used ash is accumulated within the filter, which can clog it and therefore cause less efficient filtering. When the filter is clogged, cleaning is needed, which together with testing are the main steps considered for remanufacturing of a DPF (Ishizawa et al., 2009). Figure 4 below shows a picture of a DPF.



Figure 4. Picture of a DPF (Volvo Group, 2026c)

4.2. Component Description - Engine

The engine included in the study is a diesel engine, which is known for its high efficiency (Liu et al., 2017). It is a complex component consisting of hundreds of subcomponents and a weight of around 1000kg. The engine is a dynamic system consisting of a foundation of fixed components, while mobile parts work together to move gases to convert combustion energy into mechanical energy.

As it is used it can be deteriorated in many ways and the fouling of the engine can be caused by a great variation of reasons (Green & Lewis, 2008; Uppsala universitet, 2013). Hence, the remanufacturing process can be complex and consist of many optional ways to restore the condition to “as good as new”. To remanufacture an engine, one must disassemble it due to its many subcomponents and complex structure. The process steps for each subcomponent may vary depending on the conditions and characteristics of the subcomponent. However, the general steps of the remanufacturing of an engine are disassembly, cleaning, machining, special repairs, and testing. Special repair is a term for a variety of techniques used by the remanufacturing site to repair damaged subcomponents in the engine. The repair methods will not be introduced in this study.

The Figure 5 below shows a heavy-duty truck engine.



Figure 5. Picture of a heavy-duty truck engine (Volvo Group, 2026b)

The cylinder block and cylinder head are the two largest components and are the main housing for the combustion process in the engine. They guide gases throughout the combustion process, and other components are mounted to them, making them a base structure for the engine. Meanwhile, the crankshaft and camshaft are the two main rotating components in the engine. The crankshaft converts mechanical energy from the engine into energy that drives the vehicle. The camshaft regulates the gas exchange process within the engine. Furthermore, the EGR cooler is part of the exhaust gas recirculation system. It helps to reduce emissions from the engine by decreasing the temperature of the exhaust gases before they re-enter the engine (Volvo Group employee, personal communication)

The remaining components considered in this study are not described, but they still have important roles in the engine system. They are all necessary for the engine to operate properly and efficiently. All components mapped from the engine is presented in the list below.

1. Cylinder block (also called block)
2. Cylinder head
3. Crankshaft
4. Camshaft
5. EGR Cooler
6. Connecting rods
7. Main bearing cap
8. Rocker arm
9. Inlet manifold
10. Exhaust manifold
11. Valve cover
12. Oil sump
13. Vibration damper
14. Oil filter housing
15. EGR piping
16. Valves

17. Valve springs

18. Flywheel cover

As mentioned in the limitations, some components are excluded in both the MFA and LCA. Hence, there are more components to the engine than the ones listed above.

4.3. Component Description - Battery

The electric vehicle battery considered in this study consists of cells put together in modules. The modules are assembled to be a part of the full battery, often called the battery pack (Volvo Group employee, personal communication). One additional part of the battery is a Battery Management System. This is an electronic control unit that steers the functioning of the battery and makes sure vital functions are working properly (Sciatti et al., 2025). This is considered the brain of the battery. Within this report, the Battery Management System will be called Service Box. The Service Box together with the modules are central parts in the full battery, that also consists of for example housing, cooling systems and venting systems (Sciatti et al., 2025).

The degradation of the battery decreases the ability to store energy permanently. This can take place while the battery is in use, is charged or at rest, and it affects different parts of the cell components. To restore the condition of a battery, modules can be replaced, and hence also the poor cells. However, to refurbish a battery, several other steps of cleaning and testing must be carried out to ensure safety and quality (Sciatti et al., 2025).

The battery is classified as refurbished rather than remanufactured as it is not restored to a condition equivalent to a newly manufactured battery. Instead, it is resold based on set performance criteria.

Figure 6 shows a picture of an electric vehicle battery.



Figure 6. Picture of an electric vehicle battery (Volvo Group, 2026a)

5. Semi-Quantitative MFA

In this section, the semi-quantitative MFA is introduced. First, the goal of the MFA is presented, then the system definitions, followed by the results.

5.1. Goal of the Semi-Quantitative MFA

The goal of the MFA was to map the remanufacturing and refurbishment processes for understanding, and to provide a basis for the life cycle inventory (LCI) data collection. More specifically, the aim was to identify and illustrate the remanufacturing and refurbishment process steps, and how the components under study move through these steps. This will answer RQ1:

- What are the process steps and component flows within the remanufacturing and refurbishment of the DPF, engine and electric vehicle battery?

The MFA was not intended to provide exact quantification of all material or substance flows within the remanufacturing and refurbishment of the components. Therefore, the MFA in this study was considered semi-quantitative. This means that the analysis primarily focused on components and subcomponents rather than detailed substance-level flows. Flows of components and subcomponents were quantified where data was available, and where it was suitable for the aim of the semi-quantitative MFA.

5.2. System Definition of the Semi-Quantitative MFA

In this section, the system boundaries for the semi-quantitative MFA are explained, and the relevant flows and processes are decided.

5.2.1 Spatial and Temporal Boundary

The spatial boundary of the semi-quantitative MFA was defined as the renovator site, and included the remanufacturing and refurbishment process steps, material flows, and transports relevant to the renovations of the component.

The temporal boundary was set to 2025, and data for this year was therefore collected where available. When 2025-specific data was not accessible, the most recent available data was used as a proxy.

5.2.2 Relevant Flows and Processes

The flow of the component and potential subcomponents throughout the renovation process was included in the study, as well as the remanufacturing and refurbishment processes belonging to those components. This is except for the smaller components that are excluded, as discussed in section 3.5 Methodological Limitations. The subcomponents that were exchanged in the remanufacturing or refurbishment processes were also included as inputs and outputs to and from the remanufacturing or refurbishment processes. Components that are added or removed are visualized with dotted arrows, while the main flow of components are represented by solid arrows. Components entering or leaving the system boundary is orange dotted arrows. However, the preceding and subsequent processes of these components are not visible. The transport of the core to and from the renovator site was included.

As mentioned, flows of smaller components are not included. This is mostly applicable to the engine, where the mapped components are visible in section 4.2 Component Description - Engine. Internal transportation processes within the renovator site, as well as upstream production processes related to added materials and components, are not shown in the semi-quantitative MFA. Auxiliary material and energy resources in the remanufacturing and refurbishment processes are not shown. Instead, the focus is on components and subcomponents.

5.2.3 Data Collection for Determination of Flows of Goods

To conduct the semi-quantitative MFA, data about the remanufacturing and refurbishment processes, as well as for the flows of components and subcomponents, was needed. Therefore, an extensive data collection was done. The data collection was carried out simultaneously for the semi-quantitative MFA and the LCA, as the two methods overlap. The method for the data collection is provided in section 3.

5.3. Results of the Semi-Quantitative MFA

In this section, the results of the semi-quantitative MFA are presented for the DPF, the engine, and the battery, respectively.

5.3.1 Semi-Quantitative MFA - DPF

The semi-quantitative MFA of the DPF is shown in Figure 7 below. Below the figure, a description with text is added, explaining the steps.

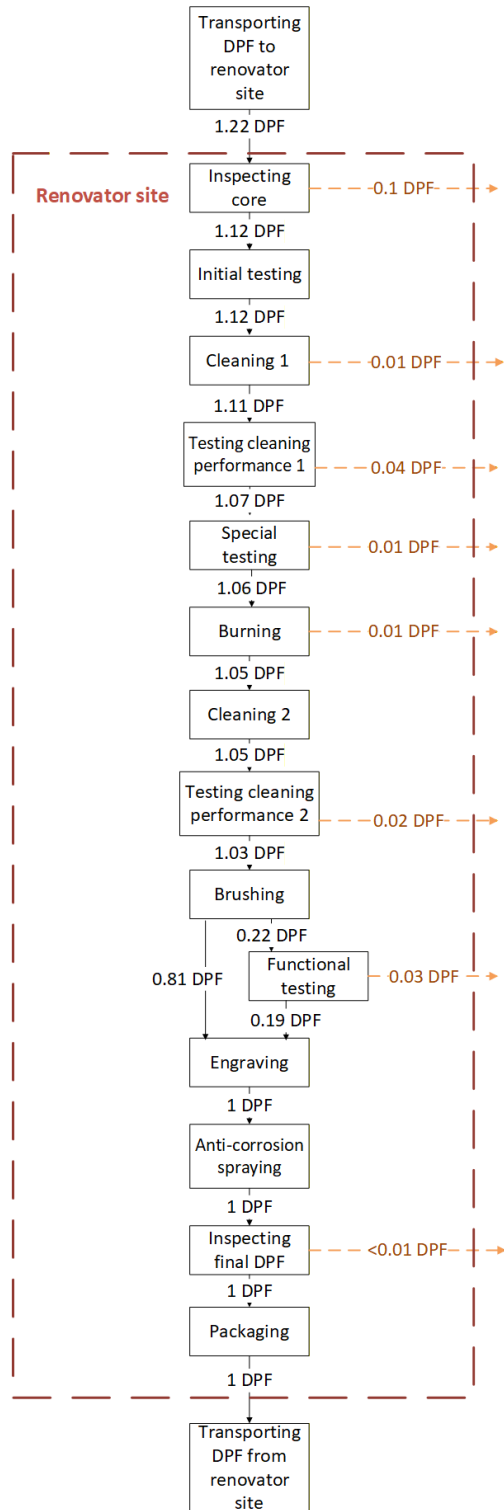


Figure 7. Semi-quantitative MFA of the DPF remanufacturing with a red dotted system boundary and yellow dotted arrows representing material going to waste management.

As seen in the figure above, the remanufacturing of a DPF mainly consists of reoccurring cleaning and testing of its performance. When the quality of the DPF does not meet the set requirements, it is scrapped. This is visible in Figure 7 above with arrows going to waste management, for example to recycling and incineration.

The initiating step within the remanufacturing process is the transportation of core to the renovator site. After delivery to the renovator site, the DPF goes through a visual inspection where it is checked for damages, such as cracks. After that, the DPF goes to a test to give an indication of the level of soot and ash in the DPF. Thereafter, the DPF goes through a cleaning to remove the soot and ash. The DPF then goes to another test to measure the performance of the first cleaning, that is, to give an indication of the level of ash and soot still in the DPF after cleaning. Another special test is then performed, to assure the quality of the component.

The DPF then proceeds to an oven, to burn remaining soot and ash still on the DPF after the cleaning. After the oven, a second cleaning is done, as well as another test is to measure the performance of the second cleaning. The DPF then enters a machine where the surface is brushed. Thereafter, depending on how many times the DPF has been remanufactured, it sometimes undergoes a special functional test to check its performance. After that, a letter is engraved onto the DPF to keep track of how many times it has gone through the remanufacturing process. The DPF is then sprayed with anti-corrosion spray. The last step in the remanufacturing process is a final visual inspection done by operators at the renovating site. The DPF is then packed and shipped to the central distribution center in central Europe.

As illustrated in the figure above, the remanufacturing of the DPF consists of cleaning, inspection, and testing intended to restore the original component, as well as transportation. It does not involve any material exchange. The DPF remains intact throughout the remanufacturing.

The mapping further shows that not all DPFs entering the remanufacturing are successfully restored. A certain amount is rejected in the remanufacturing processes due to insufficient quality or damage. Consequently, approximately 1.22 DPFs are required as input to obtain

one fully remanufactured DPF as output, while 0.22 DPFs leave the system. These DPFs go to waste management, and indicate that material losses occur throughout the remanufacturing, despite the absence of material exchange within the remanufacturing processes.

5.4. Semi-Quantitative MFA - Engine

The MFA of the engine is shown in Figure 8 below, together with a description of the component flows.

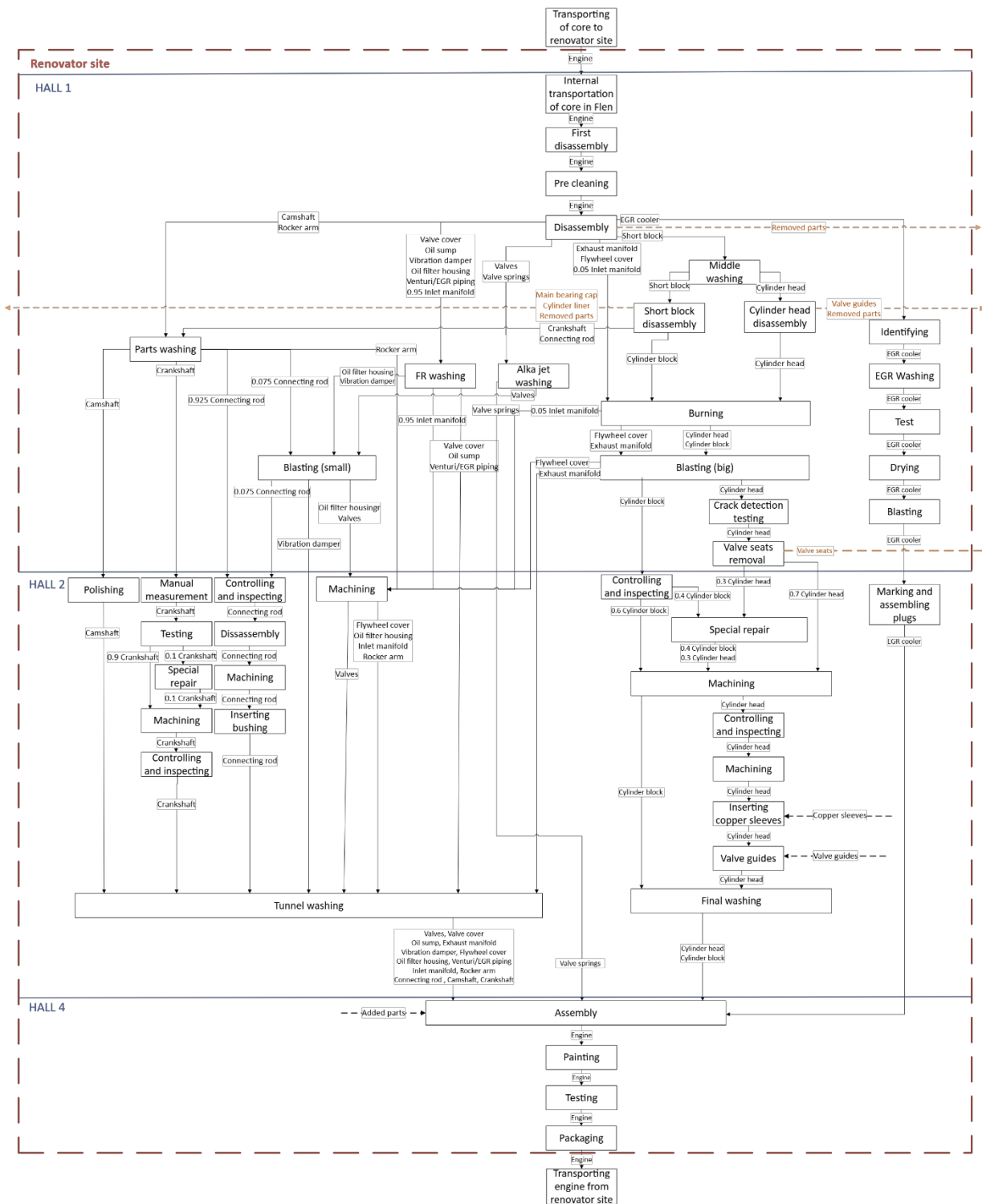


Figure 8. Semi-quantitative MFA of the engine remanufacturing, with a red dotted system boundary and yellow dotted representing material leaving the system boundary to waste management facilities. Black dotted arrows represents new material being added into the process.

The flowchart presenting the semi-quantitative MFA of the engine is split into each hall at the renovator site. The third hall is used for collection of subcomponents from the storage, which is not presented in the picture. Instead, the chart shows the flow of the components, which goes straight from Hall 1, to Hall 2, and directly to Hall 4. The written description of the flow will be divided into one initial common section for the full engine, one section for the EGR cooler, one for Cylinder Block and Cylinder Head, one for Crank Shaft, Camshaft and Connecting Rods and one for “Other” components.

Subcomponents added to the engine to replace worn out parts are represented with dotted black arrows. These subcomponents come directly from Hall 3, and hence from within the facility, which is why the arrows are started from within the border of the facility. However, these components also originate from outside of the facility, which is not an included aspect of the MFA and is therefore not illustrated.

5.4.1 Description of Initial Steps

The initial step of the semi-quantitative MFA is the transportation of the core to the renovator site. As it is received at the site, it is transported internally to its first disassembly. Some external cleaning is done as part of the demounting. This step is followed by a precleaning step, carried out in a washing machine. Thereafter, the engine is disassembled into subcomponents which takes different routes until the final assembly step. Even though the subcomponents are split up to different flows, the same parts that entered the remanufacturing site together will end up in the same assembled engine again, with exceptions for the subcomponents that must be exchanged.

5.4.2 Remanufacturing Flow of the EGR cooler

After engine disassembly, the EGR cooler is identified, which means that the specific variant of EGR cooler is determined. It is also visually inspected. Thereafter, it goes into a washing machine, before the functioning of the component is tested. The EGR cooler is then dried before it is blasted with plastic media. Finally it is assembled and marked before it is ready for the full engine assembly.

5.4.3 Remanufacturing Flow of the Cylinder Block and Cylinder Head

To follow the flow of the cylinder head and cylinder block, in Figure 8 from the disassembly step, one must follow the flow of the Short block and Cylinder head on the right-hand side of the disassembly process. The short block consists of the cylinder block as its main component, accompanied by the crankshaft, connecting rods, main bearing cap and cylinder liner. The short block and cylinder head goes through a washing machine called the middle wash. They are washed one at a time and are thereafter separated.

The cylinder head is disassembled, and the valve guides are removed. In parallel, the short block is disassembled with the cylinder block as one output flow, while main cap bearing and cylinder liners are scrapped, and the crankshaft and connecting rod goes to a washing machine. The flow of the crankshaft and connecting rod will be revisited in the following section.

The cylinder head and cylinder block goes into a common oven where components of up to eight engines can be burned at ones. This is run for approximately 8-10 hours and aims to burn dirt and grease so that it can easier be removed in the subsequent step. In the blasting process step, blasting media is projected onto the component to remove the dirt and grease that was burned in the oven. Before moving on to Hall 2 the cylinder head goes through a crack detection test, and the valve seats are removed and scrapped.

As the components enter Hall 2, the flow of the cylinder head is immediately separated, where 70% goes directly to a machining step. The other 30% goes through a special repair method. Thereafter the components goes through the machining, meaning that all cylinder heads pass through this specific machining step.

When the cylinder block entered Hall 2, a control and inspection of the component take place before the flow is separated. 60% goes straight to the machining process, and the other 40% goes to special repair before the machining. The cylinder block is then ready for a final wash in Hall 2, while the cylinder head goes through several more process steps before reaching the washing machine. First up, it is controlled and inspected. Then it goes through machining, shaping the part to make sure it will function properly in the engine. Copper

sleeves and valve guides are added before the cylinder head is washed in the final washer. The cylinder head and cylinder block are always washed separately in this machine. Thereafter, the two components enter Hall 4 for reassembly.

5.4.4 Remanufacturing Flow of Camshaft, Crankshaft, Connecting rod

The flow of the camshaft, crankshaft and connecting rod starts with disassembly of the full engine, where the camshaft together with the rocker arm is disassembled. The crankshaft and the connecting rod are disassembled in the short block disassembly step, and together with the camshaft and the rocker arm they go through a washing machine, called parts washing. After that washing, the parts have separate flows. Starting from the left in Figure 8, the camshaft goes to a polish in Hall 2, and after that directly to the tunnel washer.

The crankshaft goes into Hall 2, where it follows a number of steps. First the crankshaft is measured manually, and this is followed by a quality testing. After this, 10% of the crankshafts go through special repair, while the rest goes directly to the subsequent step. The subsequent step is machining, and this is followed with a control and inspection. The last step in Hall 2 for the crankshaft is the tunnel washer.

The flow of the connecting rod after the parts washer starts with a process where 7.5% of the connecting rods go to blasting, and the rest of the connecting rods go directly to controlling and inspection. After that, the connecting rod is disassembled before going through machining. The bushing for the connecting rods are in a freezer, and inserted before the connecting rod goes to the tunnel washer.

The flow for the rocker arm that also goes through the parts washer is explained in the following section.

5.4.5 Remanufacturing Flow of Other Components

This section introduces the flow of all other components in the flow chart. This includes the rocker arm, valve cover, oil sump, vibration damper, oil filter housing, venturi/EGR piping, inlet manifold, valves, valve springs, exhaust manifold and flywheel cover. Several flows follow a similar structure. The valves, 95% inlet manifold, oil filter housing, vibration

damper, and rocker arm all goes through an initial washing, then blasting and/or machining before entering the tunnel washer. Meanwhile the valve cover, oil sum and venturi/EGR piping went straight from one washer to the tunnel wash.

For the rest of the parts considered as Others, the exhaust manifold, flywheel cover and 0.5% of the inlet manifold are burnt in the oven, before going through the blaster. The flywheel cover and 0.5% of the inlet manifold are machined before all three components are washed in the tunnel wash.

The valve springs are washed in the Alka jet washer and are thereafter ready for the engine reassembly, without going through any other process steps.

5.4.6 Description of Final Steps

The reassembly of the engine takes place in Hall 4. Before this stage, additional parts required to create a fully remanufactured engine is collected from Hall 3. No assembly, machining or other modification to the engine is done in Hall 3, why the hall is not included in the MFA. Instead, for simplicity, these added parts enter directly in Hall 4 during the reassembly process.

The reassembly occurs on several subassembly lines, where the subcomponents are reassembled, and in final reassembly line where parts are reassembled sequentially onto the engine. Once the engine is fully reassembled, it is painted. The engine then undergoes testing, where the engine runs under various operating conditions. Since the engine is running, heat is generated. This heat is recovered and transferred with heat pumps, supporting heating of the facility. After testing, the engine is packed and transported from the renovator site to the central distribution center.

5.4.7 Analysis and Interpretation

As illustrated in Figure 8, the remanufacturing of the engine is complex and consists of many subcomponents. As opposed to in the remanufacturing of the DPF, the engine has subcomponents that need to be replaced because of technical specifications or because they are worn and cannot be repaired. This is shown by the black dotted arrows displaying Added

parts and the dotted orange arrows leaving the system boundary. The same subcomponents that need to be removed are also being replaced with new corresponding ones. The replaced subcomponents consist of many different materials, and as the specific material amount of material that is replaced is confidential, the amounts of replaced subcomponents cannot be displayed in this study. However, the majority of the weight of the engine's material is saved.

5.5. Semi-Quantitative MFA - Battery

The semi-quantitative MFA of the battery is shown in Figure 9 below. A description of the flow is also added in text with some additional details explaining the steps.

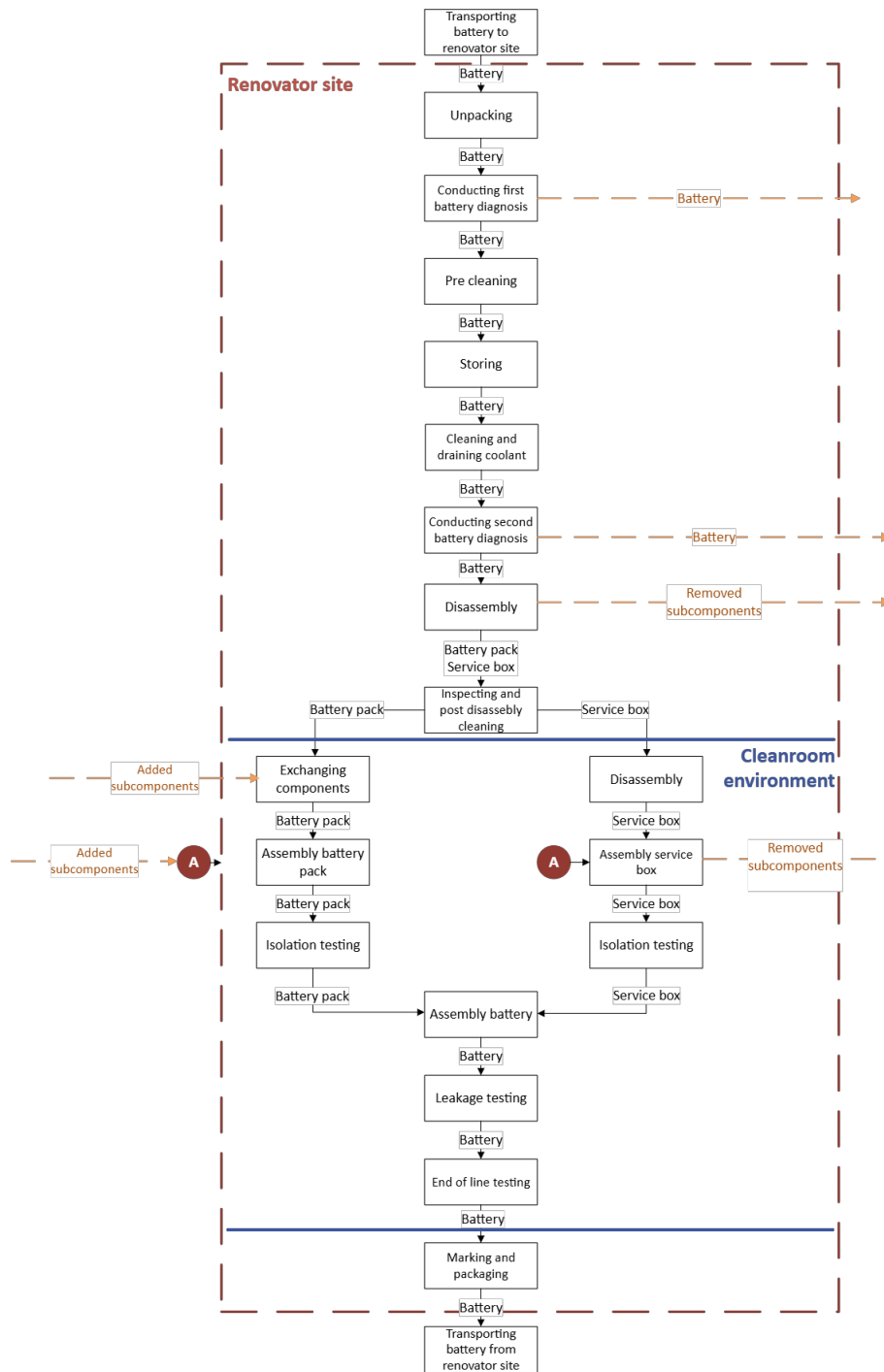


Figure 9. Semi-quantitative MFA of the battery refurbishment with a red dotted system boundary and yellow dotted arrows representing material entering the renovator site or leaving the site to waste management

The refurbishment of the battery starts with transportation of the core to the renovator site. Thereafter, the refurbishment is done according to the Figure 9 above, and the steps are here explained more in detail. Along the refurbishment process, there also is a number of software updates, that are not specified in the flowchart above.

After arrival at the renovator site the battery is unpacked and registered into an internal system. Thereafter, a diagnosis is done of the condition of the battery by evaluating the condition of the battery, checking for fault codes and for physical damage. If the battery does not live up to the set safety and quality standards, it can at this point be sent to recycling. In the flowchart above, this is shown by orange arrows leaving the system boundary. After passing the quality check, a cleaning step is carried out using vacuum cleaning on external parts of the battery. The batteries are then stored until the renovator site has the capacity to receive and begin refurbishment of the specific battery.

After storage, a diagnosis test similar to the initial one is conducted to ensure that no new issues have occurred during storage, before starting the refurbishment process. Based on the updated diagnostic results, the batteries are grouped into different categories depending on the condition of the battery pack, allowing consumers to choose the desired battery performance level.

In the disassembly step, the service box and battery pack are separated. Depending on its condition, specific subcomponents of the battery, for example modules in the battery pack, might need replacement. There are also a number of parts that are always exchanged due to technical requirements. The subcomponents deemed substandard are removed from the battery pack and sent to waste management. Replacement of these components with new ones happens at a later stage. The disassembled service box and battery pack are then being inspected and cleaned before the subcomponents enter a clean room environment. The flow of the two components is separated as they enter the cleanroom.

The initial step for the service box in the separated flow is disassembly. The service box is never disassembled outside the cleaning room environment due to its high cleanliness standards to ensure safe functioning. Following the disassembly, the new materials or

components are added to the service box, and removed parts are sent to waste management. An isolation test is carried out on the service box to ensure proper electrical flow through the component.

The separate flow of the battery pack starts with replacement of the removed modules and subcomponents. After that an isolation test of the battery pack is carried out. The battery pack and the service box are then reassembled again.

Thereafter, the assembled battery goes through a leakage test, assuring no liquid will leak and cause damage to the electronics of the battery. Finally, there is an end of line testing, which is a functional test of the battery pack to ensure that the battery meets all requirements. At the end of this test, the state of charge of the battery is adjusted to ensure that it can be transported using all modes of transportation. The battery then leaves the cleanroom environment and is marked and packaged before it is transported away from the facility.

6. Life Cycle Assessment

The life cycle assessment in this study is guided by the ISO 14040 and 14044 (ISO, 2006). First, the goal is presented, then the scope and modelling requirements, followed by the LCA results, including the LCI and the LCIA results.

6.1. Goal and Scope Definition

The goal of the LCA is to quantify the environmental impact associated with remanufacturing processes of the heavy-duty truck DPF and the engine at Volvo Group's two renovator sites in Europe. The LCA supports the broader aim of this thesis: to map circular process steps, and assess the associated environmental impact. The result is used to highlight possible areas of improvements within the system. The life cycle assessment answers RQ2 and RQ3:

- What are the environmental impacts associated with the remanufacturing and refurbishment of the DPF and the engine?
- What are the hotspots in the circular processes of the two environmentally assessed components, and how do specific process steps compare in terms of their environmental contribution?

The intended audience of the results includes internal stakeholders at Volvo Group involved in circular operations, sustainability assessment, and decision making. The study is also directed to examiners and students at Chalmers University of Technology, as it will be published on the university's internal database for master's theses. The intended audience of the results are also technical experts interested in remanufacturing of truck components and the associated environmental impacts.

The scope and modelling requirements of the study include the description of the product system, functional unit, reference flow, system boundaries, geographical and temporal scope,

impact categories, allocation and cut-off criteria, and the setup for the sensitivity analysis. This is introduced in the following sections.

6.1.1 Product System and Modelling Approach

The subject of the study is the remanufacturing of the DPF and engine within Volvo Group.

The study models the process steps included in the remanufacturing of the selected components, the input and outputs of each process step including the upstream supply of materials and subcomponents, as well as transportation distances. The study is an attributional LCA, describing the environmental burdens of the defined remanufacturing processes under current conditions. It does not include any consequences of changes in the system, such as increased remanufacturing activities (Baumann & Tillman, 2004).

The LCA is conducted using openLCA, together with the database Ecoinvent 3.12 Cutoff Unit (2025-12-19).

6.1.2 Functional Unit and Reference Flow

The aim of the LCA in this study is to evaluate the environmental impact of a remanufactured DPF and engine. The function of the system is to provide remanufactured spare part components for trucks that fulfill the same technical function as a corresponding new component.

The functional unit is therefore one remanufactured spare part, specifically one DPF and one engine respectively, being remanufactured and delivered to and from the renovator site in 2025, providing equivalent functionality to a new part.

The reference flow is the quantified amount of product and supporting flows required to fulfil the functional unit (Baumann & Tillmann, 2004). The reference in this study consists therefore of the total inputs and outputs associated with remanufacturing of the DPF and the engine. This includes electricity, fuels, auxiliaries, replacement and added materials and subcomponents, transport and waste treatment per remanufactured spare part.

6.1.3 System Boundaries and Flowchart

The system boundary of this study is defined as the remanufacturing system and includes the remanufacturing processes mapped in the semi-quantitative MFAs, as well as the added material and upstream processes, transportation and a selection of the waste management, which is further explained below. This includes remanufacturing processes, transportation, auxiliary materials that are used in the process. For the engine, it also includes material that is exchanged in the remanufacturing process. The remanufacturing processes refer to the process steps taking place within the remanufacturing facility. These processes are all within the renovator site's borders, which are shown in the results of the semi-quantitative MFAs, found in Figure 7 for the DPF and Figure 8 for the engine.

The LCA does not include the first lifecycle of the component, meaning when it is newly manufactured, nor the use phase.

Flowchart:

Figure 10 presents an overview of the product system in the remanufacturing of a component, and the included life cycle stages. The system boundary is shown by the red marking.

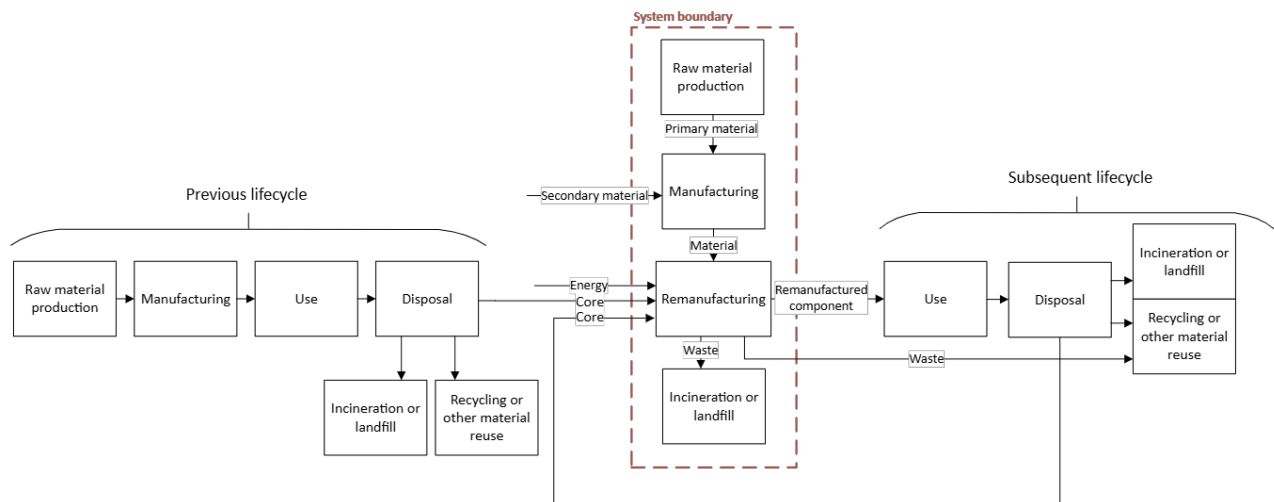


Figure 10. System boundary of the LCA

On the left in the figure, the first lifecycle of the component is shown. Within the system boundary is the Remanufacturing, occurring at the renovator site. Inputs and outputs to this are shown by the labeled arrows. Inputs to the remanufacturing are energy, material (primary and secondary), and the core itself. Outputs from the system are waste, going to either incineration, landfill, recycling or other material reuse. The remanufactured component is also an output from the remanufacturing. On the right in the figure, the second lifecycle of the component is visible.

Below is a more detailed description of which processes are included and excluded from the product system.

Included activities

Component logistics:

- Transport of the collected core from the national core hubs to the central distribution center
- Transport of the core from the central distribution center to the renovator site
- Transport of the remanufactured component from the renovator site back to the central distribution center

These flows are also presented in Figure 2. The transportation above will be referred to as Transportation of the core, even though the component after remanufacturing is no longer called core.

Operations at renovator site:

- The ones included in the results of the semi-quantitative MFA in Figure 7 and Figure 8.

Upstream processes for new subcomponents that are replacing used subcomponents:

- Raw material extraction and processing
- Manufacturing of new subcomponents and materials
- Transport of the new subcomponents to renovator site

When referring to new subcomponents, the term Material Exchange is used as the old, worn-out part is exchanged with a new corresponding one.

Waste treatment:

- Waste treatment processes for the waste sent to landfill and incineration
- Transportation of waste sent to landfill, incineration, and recycling

Excluded activities

- The previous life cycle of the core as seen in the figure above
- The use phase after remanufacturing
- Waste treatment processes of waste that is sent to recycling
- End-of-life of the remanufactured part
- Packaging materials
- Capital goods and infrastructure
- Subcomponents used for replacements that have had a previous life and has been remanufactured

The last bullet point refers to cases where a subcomponent cannot be reused and needs to be replaced. In such cases, it is replaced either by a newly manufactured equivalent subcomponent or by a remanufactured equivalent subcomponent originating from another core. In the latter case, no environmental burden is allocated to the replacement part, as the impacts associated with its previous life cycle are considered to have already been accounted for. Additionally, the environmental burden of renovating this replacement spare part is not accounted for, which contributes to underestimation of the environmental impact.

6.1.4 Geographical and Temporal Scope

The geographical scope of the study is limited to Volvo Group's internal remanufacturing activities at the European sites, one in Sweden and one in France.

From these two sites, primary data was collected. Upstream supply chains and transport are sometimes global depending on the origin of materials used in the remanufacturing.

This is a retrospective LCA, which aims to calculate the environmental impact of remanufacturing done in 2025. The most recent available data (primarily 2025) was used, and interview and data collection were conducted during the spring 2026.

6.1.5 Allocation and Cut-Off Criteria

This study includes process steps with multiple outputs, or situations where the only available data was one shared input for several outputs, requiring the environmental burden to be allocated across multiple components. The allocation method used was mass allocation, where this physical relationship determined the share of the total environmental burden that was allocated to each component (Baumann & Tillman, 2004).

A simple cut-off method is applied in the LCA. Under this approach, the original manufacturing and use phases of the returned core are excluded, as these environmental burdens are attributed to the component's first life cycle. The use phase of the remanufactured component is also excluded, as a cradle-to-gate approach is applied, and the remanufactured spare parts are assumed to deliver equivalent performance and lifetime to new components.

When a subcomponent is replaced in the remanufacturing process, with a renovated replacement spare part from another core rather than a newly manufactured part, no environmental burden is accounted to the renovated replacement spare part. The impacts associated with its previous life cycle are considered to have already been accounted for. Meanwhile, the environmental burden of renovating the replacement spare part is not accounted for either, contributing to underestimations of the results. Furthermore, end-of-life processes of the remanufactured component are excluded, as the system boundary includes processes only up to the point where the component leaves the remanufacturing system.

Waste treatment impact associated with landfill and incineration are included, and the connecting transportation. In contrast, waste sent to recycling is only included up to the point

where the material reaches a recyclable state, which includes transportation to the recycling site. Subsequent recycling processes are excluded, since the environmental burden shifts to the product system that utilizes recycled material.

Capital goods and infrastructure are excluded from the system boundary, in line with common LCA practice (Baumann & Tillman, 2004).

6.1.6 Impact Categories and LCIA Method

In an LCA, one should ideally cover a wide range of environmental impact categories (Baumann & Tillman, 2004). One should also choose the impact categories that are most applicable to the study (Finnveden, 2009).

In this study, the selection of impact categories was guided by the TranSensus Life Cycle Assessment guidelines, that create a harmonization of LCA methodology for transport systems across Europe (TranSensus LCA, 2025). The impact categories are together aimed at providing a broad assessment of environmental impacts. The impact categories selected in this study include six out of seven impact categories that are mandatory according to TranSensus. The six chosen impact categories are presented in Table 2 below. The table is adapted from the TranSensus Life Cycle Assessment guideline and has been slightly modified to reflect the scope of the study. The impact category Climate Change refers to the impact category Climate Change Total, and will be referred to as only Climate Change in this project.

Table 2. Adapted from TranSensus Life Cycle Assessment guidelines and slightly modified (TranSensus LCA, 2025)

Impact Category	Impact Category Indicator	Unit
Acidification	Accumulated Exceedance (AE)	mol H+ eq.
Climate Change	Radiative forcing as global warming potential (GWP100)	kg CO2eq
Eutrophication: freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq.

Material resources: metals/minerals	Abiotic resource depletion for elements (ADP ultimate reserves)	kg Sb eq.
Particulate matter formation	Impact on human health	disease incidence
Photochemical oxidant formation: human health	Tropospheric ozone concentration increase	kg NMVOC eq.

Apart from the categories in Table 2 above, the impact category Cumulative Energy Demand (CED) is mandatory to include according to TranSensus’ guidelines. However, this category did not exist in the chosen LCIA method, and is therefore excluded from the study.

The LCIA method used for the impact assessment in openLCA was EF v3.1 (Environmental Footprint 3.1), which is a method developed by the European Commission for assessing environmental impacts across multiple impact categories (European Commission, 2024b).

6.1.7 Data Quality

Primary data was prioritized for the remanufacturing processes. Primary data should represent the studied period, and the latest data available should be used, which for this study usually meant data from 2025. The primary data was collected from Volvo Group’s renovator sites that were included in the study. For background processes, such as production of replacement materials, transport, and waste treatment, datasets from the database Ecoinvent 3.12 Cutoff Unit (2025-12-19) were used.

In all modeling, the available dataset with the most representative location was chosen. For example, the electricity mix is chosen based on the country the renovator site is located in, and fuel types and transport modes reflect the conditions of the studies system to the greatest extent possible.

Inventory data collection focused on for example, energy use, transport, waste management, and information about subcomponents added due to the replacement of worn or faulty components. Data on auxiliary materials, such as oils, detergents, and other consumables

have been collected and are included where available. While all identified flows have been included in the results, the completeness of the data depends on the information provided during the data collection process.

6.1.8 Sensitivity Analysis

This chapter introduces the sensitivity analyses conducted in the study. The analyses aim to evaluate how variations in modelling assumptions influence the total environmental impact of remanufacturing, particularly for processes that have a substantial contribution to the overall impact. In addition, the sensitivity analyses address processes associated with high modelling uncertainty, caused either by limited process understanding or mismatches between LCA datasets and actual operating conditions.

Transportation is one area where the datasets used in the LCA are not fully representative for the actual transport conditions. Therefore, transportation modelling is examined in greater detail through sensitivity analyses. This also addresses RQ4:

- How sensitive are the Climate Change impact results to assumptions regarding transportation modelling?

The analyses are described in more detail in section 6.3.1 for the DPF and section 6.4.1 for the engine.

6.2. Inventory Analysis

The lifecycle inventory analysis (LCI) involved the collection of both descriptive and quantitative data required to model the remanufacturing systems. The previously conducted semi-quantitative MFA, presented in Chapter 5, served as the basis for the inventory analysis by identifying relevant remanufacturing process steps and associated component flows. The inventory data collection included information regarding process inputs and outputs such as energy use, auxiliary materials, transportation, waste flows, as well as material exchange if subcomponents need to be replaced.

6.2.1 General Data Collection Strategy

The inventory data collection strategy was based on the general data collection methodology described in Chapter 3. The life cycle inventory primarily relied on primary data collected from the renovator sites through internal databases, documentation, interviews, and study visits.

Primary data were prioritized whenever available, as they were considered the most representative of the actual remanufacturing operations. When primary data were unavailable or could not be collected within the project timeframe, secondary data from literature, other technical documentation, and secondary data from Ecoinvent was used.

The prioritization order for the data is as follows:

1. Primary data from internal databases, estimations and measurements from operators (including data from technical specifications and user manuals)
2. Secondary data such as user manuals on similar machines and estimated top effect
3. Secondary data, Ecoinvent
4. Secondary data, literature based

6.2.2 Inventory Modelling and Specific Data Collection Strategy

In this section, modelling and data collection for the remanufacturing processes, material exchange, transportation, and waste flows are described in more detail.

6.2.2.1 *Modelling of the Remanufacturing Processes*

In this section, certain modelling choices and setups regarding the Remanufacturing Processes are included. The data collection for the Remanufacturing Processes was extensive and included a lot of modelling choices. The process steps were divided into groups, which together with inputs and outputs are presented later in this chapter.

Common inputs and outputs were electricity and compressed air, as well as different auxiliary materials, and the modelling and data collection of this will be explained more in detail here.

Energy consumption data were collected and estimated using several different approaches depending on data availability and measurement possibilities. For example, sometimes electricity data for a specific machine used in the Remanufacturing Processes was available as measured data over year 2025. In cases where direct measurements were unavailable, energy use was estimated using machine power rating plates together with operating time and utilization factors. The utilization factors represented the difference between maximum rated power and actual operating conditions. These factors were derived either from measurements conducted during the study, as explained in section 3, or estimated when the measured utilization factors were not deemed to be applicable to the specific machine.

Electricity consumption was modelled in Ecoinvent using the datasets:

market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - SE

Or

market for electricity, medium voltage | electricity, medium voltage | Cutoff, U – FR

depending on the location of the renovator site.

Many Remanufacturing Processes had compressed air as input. Air consumption was estimated based on the technical specifications of the air tools used in combination with operating time. In some cases, data of compressed air were only available in the form of electricity consumption. Compressed air was modelled in Ecoinvent as:

market for compressed air, 700 kPa gauge | compressed air, 700 kPa gauge | Cutoff, U – RER

Auxiliary materials were also common in the Remanufacturing Processes. This includes, for example, oils, lubricating greases, absorbents, water, detergents, and blasting material. The consumption of auxiliary materials was primarily estimated based on information provided by operating personnel. In some cases, the only available data was of internal documentation reporting the quantities of materials purchased in 2025. These annual quantities were allocated to the studied remanufactured components based on production volumes.

Packaging materials were excluded from the assessment and were therefore not included in the inventory modelling.

Specific modelling choices for the Remanufacturing Processes are presented Appendix A: Inventory Results - DPF and Appendix B: Inventory Results – Engine. Note that the inventory modelling choices are not always shown because of confidentiality of the Remanufacturing Processes.

6.2.2.2. Material Exchange Modelling

As mentioned previously, the Material Exchange refers to the new material that is added to the engine, because of subcomponents that needs to be replaced in remanufacturing. This only applies to the engine since no material is exchanged for the DPF, as explained in the result of the semi-quantitative MFA of the DPF.

Data regarding subcomponent replacement frequencies were collected from internal Volvo Group documentation specifying which subcomponents are exchanged and how often, showed by a usage factor. For components that are always replaced, a usage factor of 1 is applied. For components that are conditionally replaced because of how worn they are, statistical data from 2025 were used. For example, a replacement rate of 0.05 indicates that the specific subcomponent is replaced 5% of the times.

Material composition data for each subcomponent was extracted from internal databases. The extracted information included substance-level composition data together with the corresponding weights for each subcomponent. To retrieve the average amount of new material required per remanufactured product, each substance weight for every subcomponent was first multiplied by the corresponding usage factor. The resulting substance weights were subsequently aggregated into larger material categories. The material groups are aluminum, copper, steel, cast iron, plastics, elastomers, ceramics, and electronics.

In the inventory modelling, the raw material processing, production and transportation of the materials were included. When considered necessary, additional manufacturing processes were added for specific materials or components to better represent the actual production

processes. This was done with support from an LCA practitioner. The modelling choices are presented in the LCI results.

6.2.2.3. *Transportation*

The transportation processes included in the environmental impact assessment comprised transportation of the core (including core and remanufactured component transportation), transportation of material, and transportation to waste management facilities. Some transportations are included in the modelled input or output in the remanufacturing processes, while some transportation is modelled separately.

As mentioned, the transportation of core includes transport of the core from national core hubs to the central distribution center, and then to the remanufacturing site, as well as transport of the remanufactured component back to the central distribution center. These transports are visualized by rust colored arrows in Figure 11 below. All these transportations were modelled separately from the remanufacturing processes.

Transportation of remanufactured components from the central distribution center back to the core hubs is excluded from the modelling. This is because there is limited access to data on these distances, and the customers returning used cores are not necessarily the same as those purchasing remanufactured spare parts. Therefore, the transportation of the ingoing cores is not considered representative for the distribution of remanufactured components. Since transportation is only included up to the central distribution center on the return journey, the total environmental impact of remanufactured spare parts is assumed to be slightly underestimated.

The transportation of cores was modelled using internal logistics statistics from 2025, describing the number of cores transported from national core hubs to the central distribution center in central Europe. Assumptions regarding the transportation distances from the national core hubs to the central distribution center was approximated using online maps. Thereafter, the transport of the core continued from the central distribution center to the renovator sites. For the engine, not all returned cores pass through the central distribution center before reaching the remanufacturing site. Returned cores originating from Sweden,

Norway, and Denmark were therefore modelled without passing through the central distribution center. For the DPF, all cores were assumed to pass the central distribution center in the absence of other information.

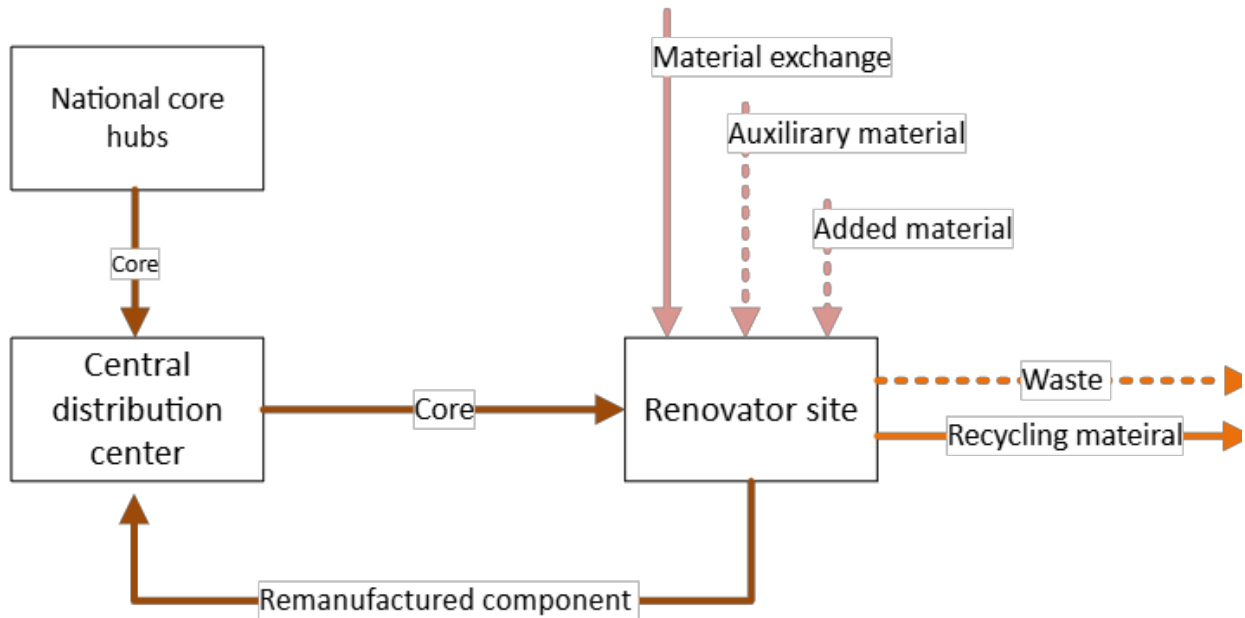


Figure 11. Illustration of different types of transportation

Transportation of material is represented by pink arrows. The material is delivered to the renovator site to be able to remanufacture the components. The material is divided into exchanged material, auxiliary material, and added material. Transportation of exchanged material includes the transportation of subcomponents to the renovator site that are used to replace worn out or old parts that must be replaced. This transportation is modelled separately from any remanufacturing process. However, the auxiliary material and the transportation of material that is directly added to the remanufactured component are included in the remanufacturing processes where they are added. Transportations that are accounted for in the remanufacturing processes are symbolized in Figure 11 with the dotted arrows.

Transportation distances for the added components for the engine’s remanufacturing process were calculated using internal Volvo Group documentation regarding supplier locations and

distances to the remanufacturing sites. This transport represents the Tier 1 supplier transportation. Upstream transportation related to raw material extraction and material production was assumed to be included in the selected modelling datasets for the corresponding materials as this was the case for most data sets used.

The material going to waste management is represented with orange arrows. It is split over recycling material and waste material. Only the transportation distance to the recycling facility was modelled separately. This is because the transportation of waste is included in the selected datasets for waste management. However, as the recycling processes themselves were excluded from the study, transportation to those had to be modeled separately.

Both road and maritime transportation were included in modelling. The dataset used for the transportation with truck is:

market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 | transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 | Cutoff, U – RER

The dataset used for the transportation with ship is:

market for transport, freight, sea, container ship, heavy fuel oil | transport, freight, sea, container ship, heavy fuel oil | Cutoff, U - GLO

6.2.2.4. Waste flows

Waste flows included replaced materials and components, wastewater from washing processes, used auxiliary materials such as oils, detergents, absorbents, blasting media, and other consumables generated during the remanufacturing processes. Whenever possible, process-specific waste quantities were obtained from internal Volvo Group documentation and operational data. In cases where process-level waste data were unavailable, waste quantities were estimated based on auxiliary material consumption, and information provided by operators or other on-site colleagues.

For replaced components and materials in the engine, the waste flows were directly linked to the calculated amount of material that was replaced. In other words, the quantity of subcomponents added during remanufacturing was assumed to generate an equivalent

amount waste sent to waste management. For the remanufacturing of the engine, approximately 97% of the replaced material is assumed to be recycled, based on the renovator site data. Consequently, waste management for replaced materials was only modelled as transportation to recycling facilities, as the recycling processes themselves were excluded from the study boundaries.

For the other material in the remanufacturing processes, waste streams were categorized into relevant waste fractions such as wastewater (average), waste steel, inert waste, and hazardous waste.

Waste treatment processes were modelled in Ecoinvent using datasets representing the relevant waste management processes. Specific inventory modelling choices and dataset selections for waste management are presented in Appendix A: Inventory Results - DPF and Appendix B: Inventory Results – Engine.

6.3. LCA Result - DPF

In the following section, the LCA result for the DPF will be presented. Firstly, the LCI is introduced, followed by the LCIA and a hotspot analysis. The section is finalized with a sensitivity analysis.

6.3.1 LCI Results - DPF

In the following section, a selection of the life cycle inventory (LCI) data for the DPF is presented. No numerical values are presented in the inventory data due to confidentiality. First, the transportation-related inventory data are presented, followed by the inventory data for the remanufacturing process steps. The inventory data is also found in Appendix A: Inventory Results - DPF.

6.3.1.1. *LCI Results for Transportation – DPF*

Table 3 below shows the LCI result for the transportation associated with remanufacturing of the DPF, together with the dataset. It is divided into Transport of the core and Transport to recycling.

Table 3. LCI result for transportation of the DPF

Type of transport	Transport mode	Amount [tonne*km]	Dataset
Transport of the core	Truck		market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 Cutoff, U - RER
	Ship		market for transport, freight, sea, container ship, heavy fuel oil transport, freight, sea, container ship, heavy fuel oil Cutoff, U - GLO
Transport to recycling	Truck		market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 Cutoff, U - RER

6.3.1.2. LCI Results for Remanufacturing Processes – DPF

In this section, the life cycle inventory (LCI) data for the remanufacturing processes of the DPF is presented. It is presented in groups of Remanufacturing Processes with inputs and outputs together with reference and assumption.

Table 4 below shows the Remanufacturing Process groups the result is divided into, together with the ingoing Remanufacturing Process steps.

Table 4. Showing categorization of process steps used for the LCIA result for the DPF

Remanufacturing Process Group	Specific process step
Cleaning and Protecting Surfaces	Cleaning 1
	Oven
	Cleaning 2
	Brushing

	Spraying anti corrosion spray
Testing	Initial testing
	Testing cleaning performance 1
	Special testing
	Testing cleaning performance 2
	Functional testing and engraving
Other	Internal transport - crane
	Dust collector
	Waste management, inert

In the inventory data below, no numerical values are presented. Furthermore, some types of inputs and outputs are confidential. When this is the case, the specific input/output will simply be stated as confidential. In those cases, no numerical values or units are included, nor are the references and assumptions used. If several inputs for one specific process step are confidential, the “confidential” label will only be shown once.

Table 5 below shows the Remanufacturing Processes for the remanufacturing process group Cleaning and Protecting Surfaces, together with input and output.

Table 5. LCI result for the Cleaning and Protecting Surfaces category of the DPF

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Cleaning 1		Confidential				
	Output	Waste: soot and ash		kg	Assumed together with Volvo Group employee	market for hazardous waste, for incineration hazardous waste,

						for incineration Cutoff, U - RER without CH
Oven	Input	Electricity		kWh	Rating plate. Assumed utilization factor 0.5.	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR
Cleaning 2		Confidential				
	Output	Waste: soot and ash		kg	Assumed together with Volvo Group employee	market for hazardous waste, for incineration hazardous waste, for incineration Cutoff, U - RER without CH
Brushing	Input	Electricity		kWh	Measured data from year 2025	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR
		Confidential				
Spraying anti corrosion spray	Input	Anti- corrosion spray – inputs confidential		kg	Assumptions from internal documentation	Confidential
	Input	Electricity		kWh	Measured data from year 2025	market for electricity, medium voltage electricity,

						medium voltage Cutoff, U - FR
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Table 6 below shows the Remanufacturing Processes for the remanufacturing process group Testing, together with selected datasets.

Table 6. LCI results for the Testing category of the DPF

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Initial testing		Confidential				
Testing cleaning performance 1		Confidential				
Special testing	Input	Electricity		kWh	Rating plate. Assumed utilization factor 0.5.	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR
		Confidential				
Testing cleaning performance 2		Confidential				
Functional testing and engraving		Confidential				

Table 7 below shows the Remanufacturing Processes for the remanufacturing process group Other, together with input and output.

Table 7. LCI result for the Other category of the DPF

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Internal transportation - crane	Input	Electricity		kWh	Rating plate	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR
Dust collector	Input	Electricity		kWh	Measured data from year 2025	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR
Waste management, inert	Output	Waste: part of scrapped DPFs		kg	Volvo Group Employee	market for inert waste, for final disposal inert waste, for final disposal Cutoff, U - RoW

Table 8 below shows the Remanufacturing processes that are a part of the remanufacturing of the DPF but excluded from the LCA modelling.

Table 8. Excluded remanufacturing processes for the DPF

Specific process step	Reason to not include
Inspection of core	Only eye control – no input/output
Inspection of remanufactured DPF	Only eye control - no input/output

Packaging	Outside of scope
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6.3.2 LCIA - DPF

The following section presents the LCIA results for the DPF. The results are divided into Transportation and Remanufacturing Processes. This section first shows the total environmental impact of the DPF, and this is followed by a hotspot analysis for both Transportation and Remanufacturing Processes. The sensitivity analysis is then presented.

6.3.2.1. Total Environmental Impact - DPF

The total environmental impact of remanufacturing a DPF is presented in Figure 12 below, split into Transportation and Remanufacturing Processes. In the figure, the total impact of each impact category is presented above each column, while the blocks in the columns show how much each remanufacturing activity contributes to each impact category. Hence, from the total of 0.03 mol H⁺-Eq in acidification impact, almost 60% comes from transportation. The other around 40% comes from the remanufacturing processes.

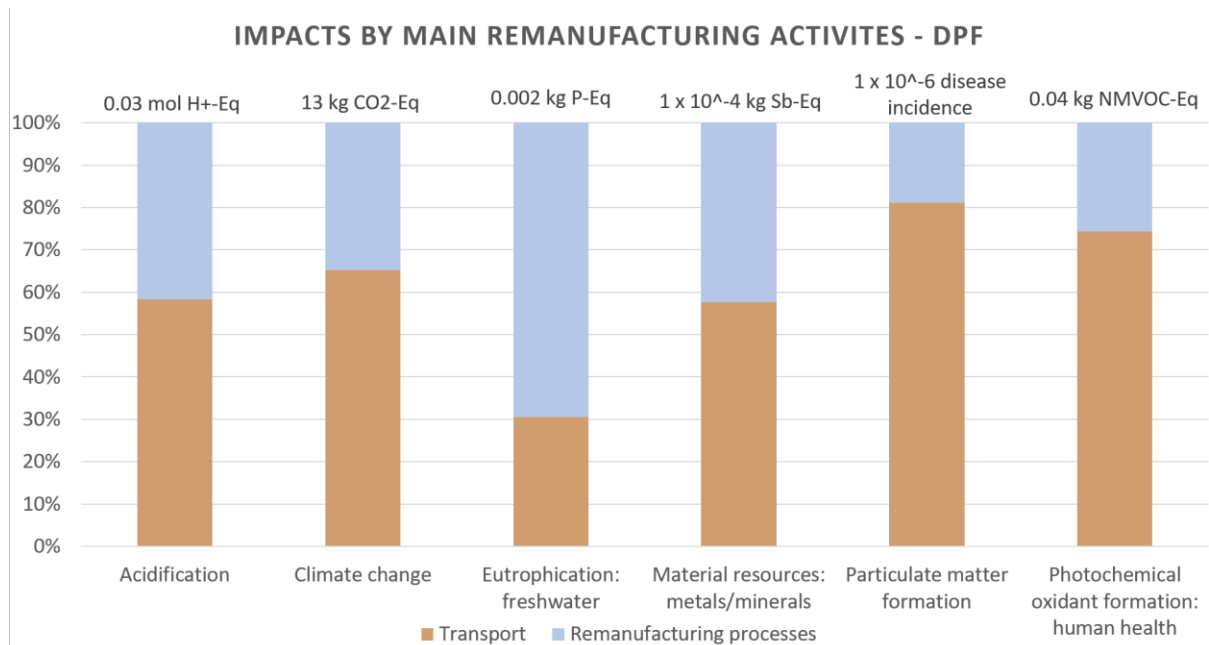


Figure 12. Impacts by main remanufacturing activities - DPF

6.3.2.2. Hotspot Analysis - DPF

Based on the results in Figure 12, Transport accounts for the largest part of the impact in each impact category except for in the category Eutrophication: freshwater, where the Remanufacturing process accounts for approximately 70%. In the impact category Material Resources: Metals/Minerals, the contribution from Transport and Remanufacturing processes is evenly distributed.

Hotspot Analysis of Transport - DPF

Within the transportation of the DPF, the Transport of Core dominates the environmental impact contribution, reaching over 99% of the contribution in all impact categories. Therefore, no figure is shown on this. However, Figure 13 below show the Transport of Core divided into the two transportation modes, transport by truck and transport by ship.

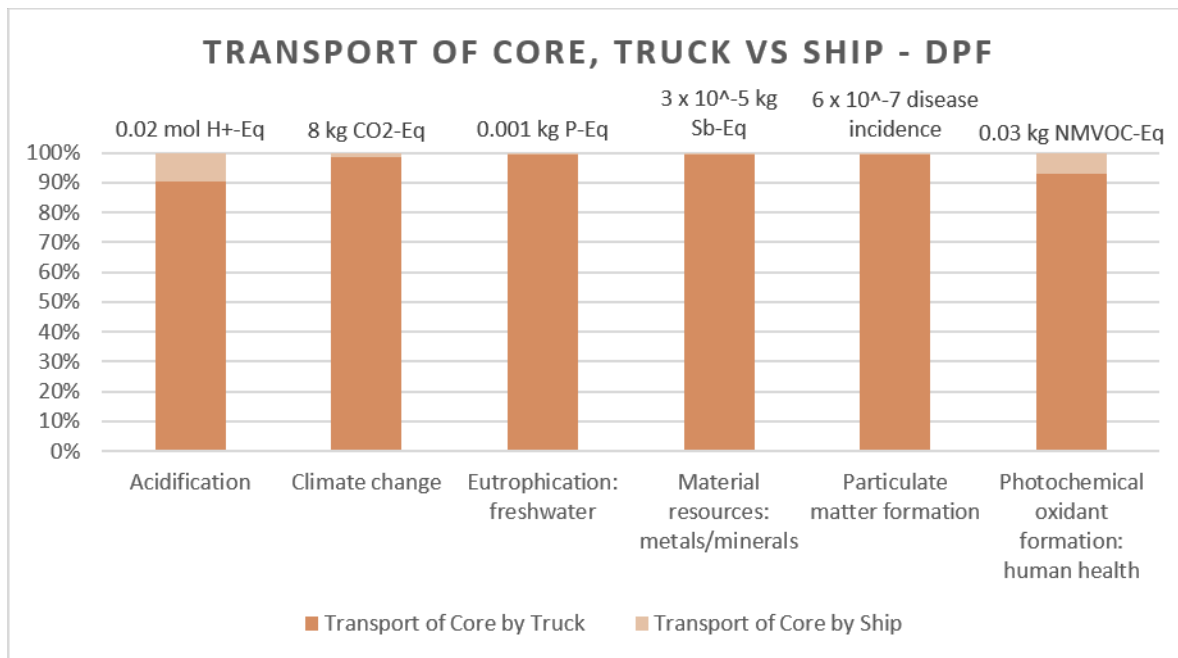


Figure 13. Hotspot analysis of Core transport split between truck and ship transportation

Figure 13 shows that the transportation carried out by truck has the largest contribution to most environmental impacts. It should be noted that this is correlated with the fact that a large share of core transportation is done by truck, as most transportation takes place in Europe.

A transportation sensitivity analysis will be done using other assumptions regarding load factors when transporting. This is presented further in section 6.3.3.

Hotspot Analysis of Remanufacturing Processes - DPF

The remanufacturing process steps within the DPF remanufacturing are divided into three groups: Cleaning and Protecting Surfaces, Testing, and Other. The categorization of ingoing remanufacturing process steps for these groups is presented in Table 4 above. The environmental impacts are presented in Figure 14 below.

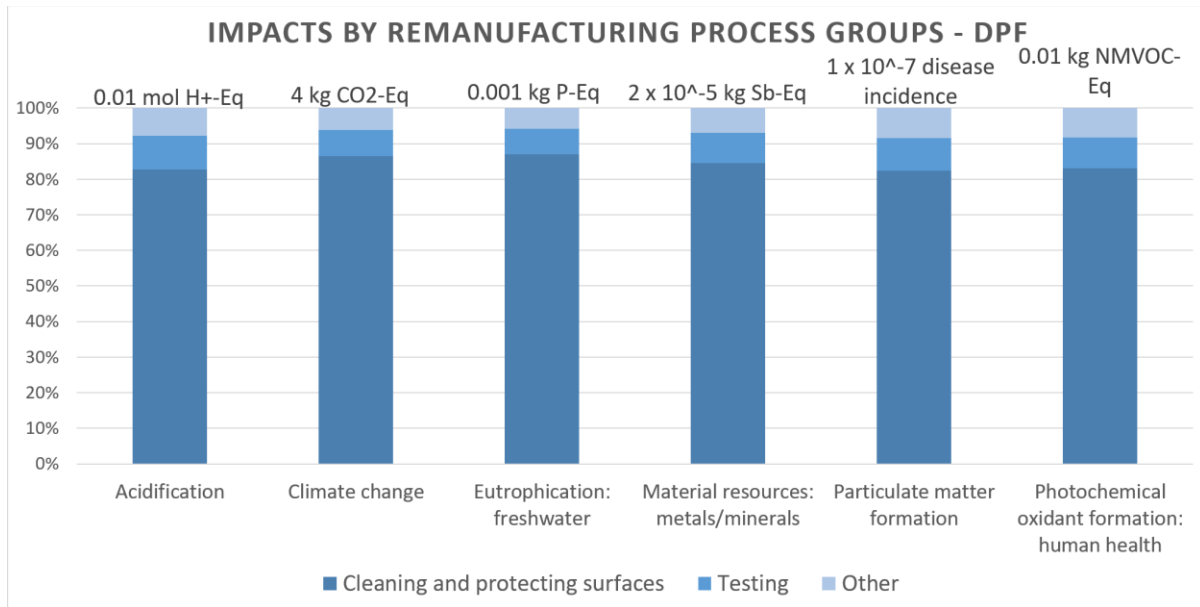


Figure 14. Hotspot analysis of impacts by remanufacturing process groups- DPF

Figure 14 above shows that the hotspot is clearly in the group Cleaning and Protecting Surfaces in all impact categories. These steps contribute to 82-87% in each impact category within the remanufacturing processes.

To further analyze the hotspot of the group Cleaning and Protecting Surfaces, Figure 15 below presents the impacts from the processes within this group in more detail.

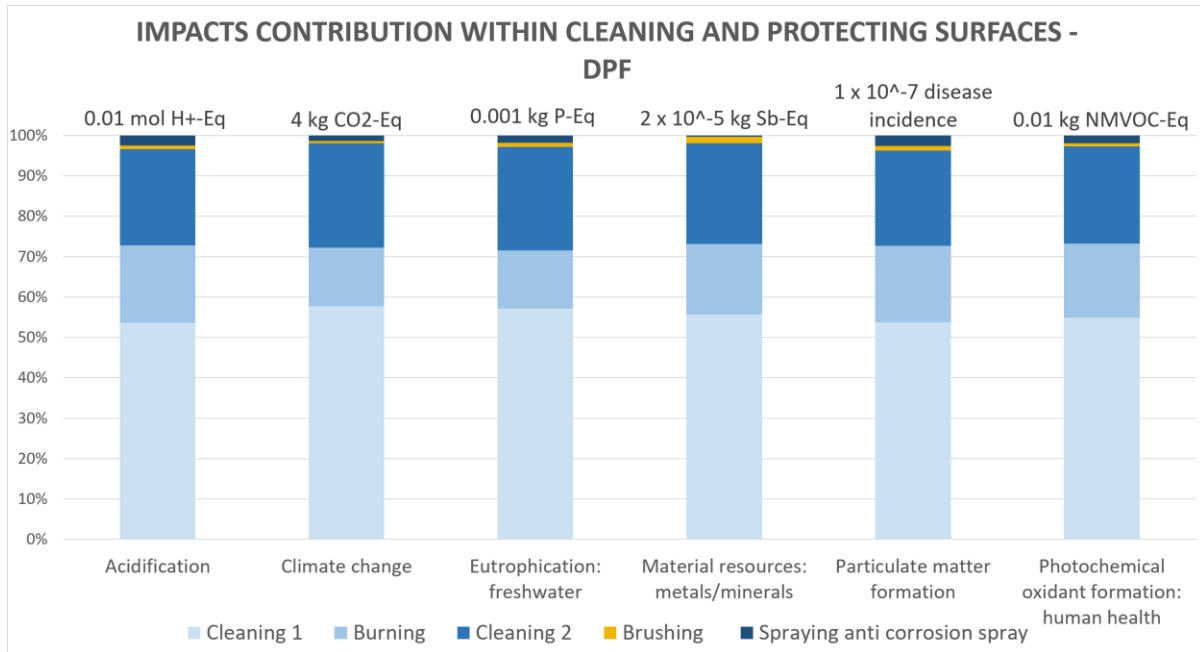


Figure 15. Hotspot analysis of the Cleaning and Protecting Surfaces processes

It can be seen in the figure that Cleaning 1 is the greatest contributor in all categories, followed by Cleaning 2 and then Burning. Due to confidentiality as well as the order of magnitude of the impact compared to the full remanufacturing of the DPF, no further analysis will be done to any of the processes in Figure 15.

6.3.3 Sensitivity Analysis - DPF

Transportation has the greatest contribution to the total impact in almost all impact categories. A sensitivity analysis is therefore done based on how well the freight capacity is utilized. Furthermore, this is a part of answering RQ4: *How sensitive are the climate impact results to assumptions regarding transportation modelling?*

The second aspect of the DPF remanufacturing is the remanufacturing processes where the Cleaning 1 within the Cleaning and protecting surfaces group accounted for the largest share of environmental impacts. Within this category, the waste treatment occurring from the process was modelled with big uncertainty. Additionally, the modelling of the waste

management for Cleaning 2 is subject to uncertainties. Hence, a sensitivity analysis is carried out on the waste from cleaning, to see how adjustments affect the impact.

6.3.3.1. Sensitivity Analysis of Transportation – DPF

The transportation associated with remanufacturing of the DPF is divided into transportation of the core, and transportation to recycling facilities. For the truck transportation, the dataset *transport, freight, lorry, 16-32 metric ton, diesel, EURO 6* is used, consisting of a 10-tonne vehicle carrying a 5.79-ton load. However, the background data for this shows that the truck can weigh 28 tons, meaning that the maximum load capacity is 18 tons.

In the default dataset, the load of 5.79 tons results in a *load factor* of $5.79 / 18 = 0.322$. In contrast, Volvo Group's transportation is often more optimal, which suggests that the average load factor is higher than 32%. This difference, combined with the fact that transport accounts for a rather large share of the total environmental impact, gives reason to analyze this further. The analysis focuses on truck transport, as it represents a substantial share of the total climate impact from transportation, compared to ship transport.

The sensitivity scenarios are defined based on a percentage of the maximum load capacity, established at 18 tons. The core transportation is modeled across the widest range of scenarios. This is because it has the highest impact, and it is also assumed that the truck could travel full load both to and from the renovator site. Therefore, the Transportation of Core can reach a 100% load factor in the scenario modelling. In contrast, Transport to Recycling has a maximum load factor of 50% in the analysis, since it is assumed to have empty returns.

The scenarios are named based on the scenarios plotted, with names of RX/CY where R stands for Recycling transportation and X is the load factor used for that transport, and C represents Core transportation and Y the load factor for that transport. In the first scenario, R50/C32, the recycling transportation reaches a 50% load factor, while the core transport is kept at 32%. The best scenario is R50/C100, meaning a scenario where the recycling transport reaches a 50% load factor (9 tons), while core transportation reaches 100% (18 tons).

The scenarios are presented in Table 9 below, showing the load factor in % together with the load in each scenario. It is important to note that these figures represent modelling choices rather than the physical weight of specific components. They just serve as a proxy to adjust the Climate Change impact per ton-kilometer in the LCA.

Table 9. Scenarios used in the sensitivity analysis for the DPF transportation

Scenario / Type of transport	Current scenario	R50/C32	R32/C50	R50/C50	R50/C75	R50/C100
Transport to Recycling	32% 5.79 ton	50 % 9 ton	32% 5.79 ton	50 % 9 ton	50 % 9 ton	50 % 9 ton
Transport of Core	32% 5.79 ton	32% 5.79 ton	50% 9 ton	50% 9 ton	75% 13.5 ton	100% 18 ton

The load factors in the table above were used and resulted in the Figure 16 below, showing the climate change impact for the different scenarios, split between Transport of Core and Transport to Recycling.

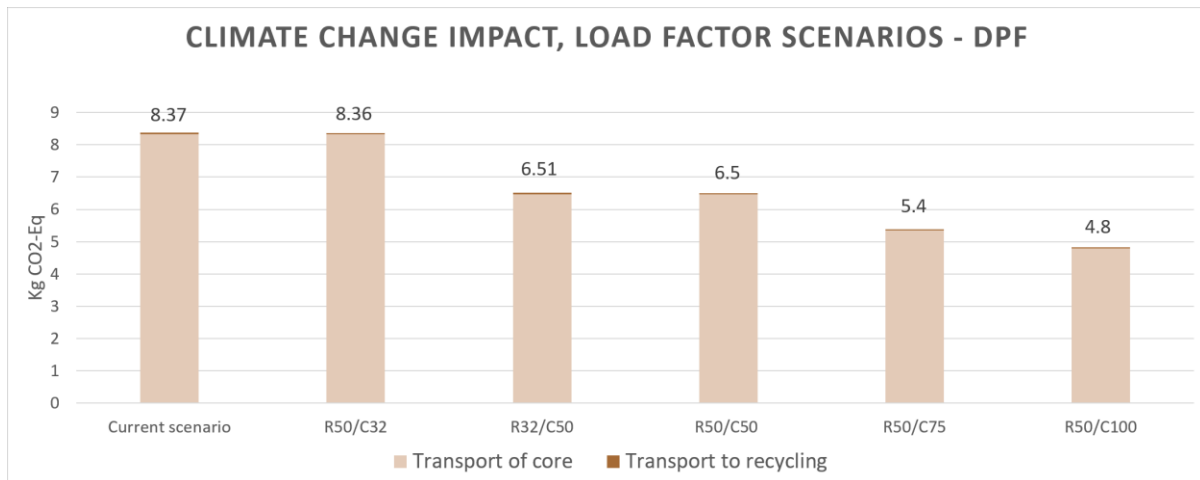


Figure 16. Sensitivity analysis of different transportation scenarios, using load factors, measured in the Climate Change impact category for the DPF

The result from the sensitivity analysis of load factors visible in the figure above shows that the load factor has a profound effect on the total emissions from transportation. In the best scenario, with a load factor of 50% for transportation to recycling, and a fully loaded truck for all core transport, the climate change impact decreases with 42% compared to the current scenario.

6.3.3.2. Sensitivity Analysis of Waste Modelling - DPF

For the DPF, soot and ash are removed during the two cleaning processes, Cleaning 1 and Cleaning 2, within the category Cleaning and Protecting Surface. In the model, this is treated as hazardous waste sent to incineration. However, the data regarding the amount of waste generated was estimated based on very limited data is therefore uncertain. In the current scenario used to model the main results, the waste generated is assumed to be 0.33 kg in Cleaning 1 and 0.17 kg in Cleaning 2. In this sensitivity analysis, these amounts are reduced by 50%, resulting in 0.17 kg of waste in Cleaning 1 and 0.08 kg in Cleaning 2.

The impact of this change on the Remanufacturing Processes is shown in Figure 17 below, alongside the Current scenario used in results presented in Figure 10.

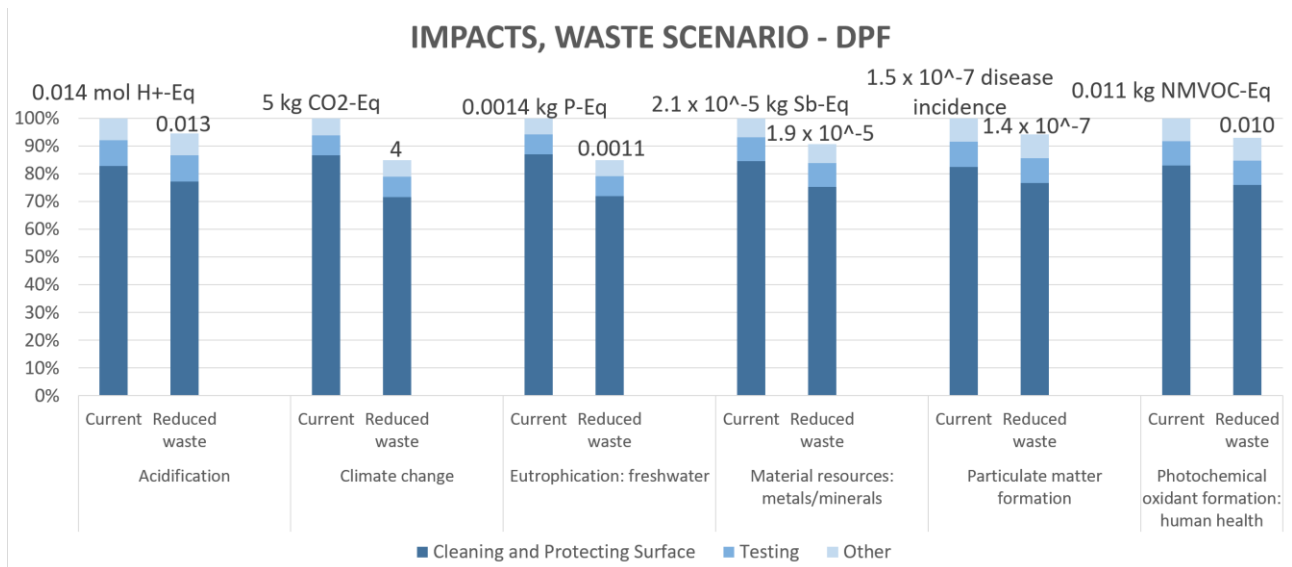


Figure 17. Sensitivity analysis of different waste scenarios in the Remanufacturing Processes, measured in Climate Change impact category for the DPF

The figure above shows that the reduction in waste is reflected across all impact categories. However, the decrease in impacts is relatively limited. In the impact category Climate Change, the scenario of Reduced waste, the total impact in the Remanufacturing Processes is decreased by 19%, and in the impact category Photochemical oxidant formation: human health, it is decreased by 9%. The figure indicates that the assumptions related to the uncertain data on the amount of waste do not influence the total environmental impact considerably for the Remanufacturing Processes.

6.3.3.3. Sensitivity Analysis, Combined Scenarios - DPF

This section combines the two scenarios presented above. That is, the optimal load factors for transportation are applied, and the amount of waste generated in the two cleaning processes is reduced by 50%. This combined scenario is referred to as *R50/100 and Reduced Waste*. The result is presented in Figure 18 below for the impact category Climate Change, and it is visible next to the Current scenario, modelled in the main result presented in Figure 12

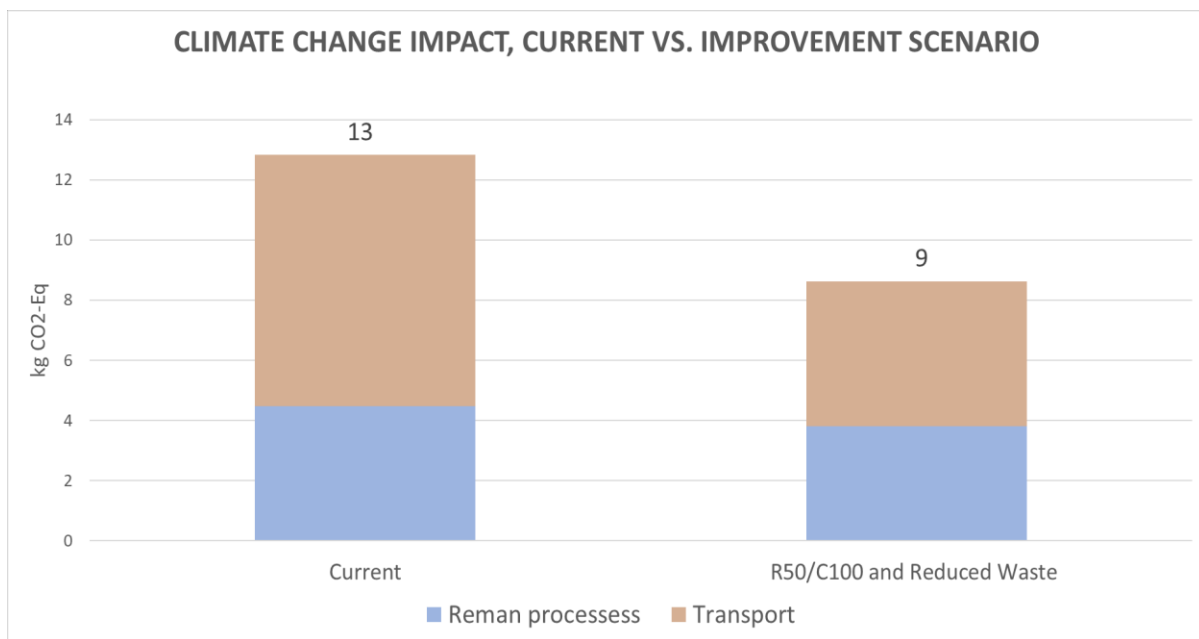


Figure 18. Sensitivity analysis of the combined scenarios of transportation and remanufacturing processes, measured in Climate Change impact category for the DPF

The figure above shows that the combined scenario results in a total reduction in Climate Change impact of 31%. The majority of this reduction originates from the decreased environmental impacts associated with transportation. After such reduction in impact from

transportation, the *relative contributions are more equal with transportation contributing to approximately 55% of the total impact compared to about 65% before.*

6.4. LCA Result - Engine

In the following section the LCA result for the engine will be presented. The LCI is introduced, and after that the LCIA and a hotspot analysis. This is followed by a sensitivity analysis.

6.4.1 LCI Results - Engine

In this section, the inventory results for the engine are presented. Firstly, the inventory data for the transport is presented, thereafter the material exchange, and then some of the LCI data for the Remanufacturing Processes. The full LCI data can be found in Appendix B: Inventory Results – Engine. Note that some of the inventory data is confidential.

6.4.1.1. LCI Results for Transportation – Engine

The LCI results for transportation are divided into three groups: Transportation of the added material, transportation of the core, and transportation of the material that goes to recycling. Table 10 below show the LCI results together with modelling choices.

Table 10. LCI results for the transportation of the engine

Type of transport	Transport mode	Amount [tonne*km]	Dataset
Transport of the added subcomponents	Truck		market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 Cutoff, U - RER
	Ship		market for transport, freight, sea, container ship, heavy fuel oil transport, freight, sea, container ship, heavy fuel oil Cutoff, U - GLO
Transportation of the core	Truck		market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 Cutoff, U - RER

	Ship		market for transport, freight, sea, container ship, heavy fuel oil transport, freight, sea, container ship, heavy fuel oil Cutoff, U - GLO
Transportation to recycling	Truck		market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 Cutoff, U - RER

6.4.1.2. LCI Results Material Exchange – Engine

This section presents the LCI results for the materials of the subcomponents that are exchanged during the remanufacturing of the engine, grouped by material category. This activity is hereafter referred to as Material Exchange and refers only to the new material added as new subcomponents. The term Material Exchange does not include the removed materials of the replaced subcomponents.

In Table 11 below, the added materials in the Material Exchange category are presented as an approximate weight share of the total amount of new material, together with the datasets used for modelling the new materials. Where applicable, the corresponding manufacturing processes are also included in the table.

Table 11. Material Exchange for the engine, shown in material groups and as a weight share of the total amount of new material

Material	Weight share of total mass [%]	Dataset	Dataset for Manufacturing process
Steel	60	market for steel, low-alloyed steel, low-alloyed Cutoff, U - GLO	market for metal working, average for steel product manufacturing metal working, average for steel product manufacturing Cutoff, U - GLO

Cast iron	20	market for cast iron cast iron Cutoff, U - GLO	-
Aluminium	10	market for aluminium, cast alloy aluminium, cast alloy Cutoff, U - GLO	market for metal working, average for aluminium product manufacturing metal working, average for aluminium product manufacturing Cutoff, U - GLO
Plastic	5	market for polypropylene, granulate polypropylene, granulate Cutoff, U - RER	market for injection moulding injection moulding Cutoff, U - GLO
Copper	2	market for copper, cathode copper, cathode Cutoff, U - GLO	market for wire drawing, copper wire drawing, copper Cutoff, U - GLO
Elastomers	<1	market for tube insulation, elastomere tube insulation, elastomere Cutoff, U - GLO	-
Ceramic	<1	market for ceramic tile ceramic tile Cutoff, U - GLO	-
Electronics	<1	market for electronics, for control units electronics, for control units Cutoff, U - GLO	-

6.4.1.3. LCI Results for Remanufacturing Processes – Engine

In this section, selected life cycle inventory (LCI) data for the remanufacturing of the engine are presented. The Remanufacturing Processes are divided into groups: Internal Transportation, Inspection and testing, Washing, Machining and Special Repair, Blasting and Burning, Assembly and Disassembly, and Others. In this section, Table 12 first describes the process groups and steps included in the different groups. After that, the LCI for the remanufacturing process group Testing is shown together with the modelling choices. The full LCI can be shown in Appendix B: Inventory Results – Engine. Note that some of the LCI

data is confidential, such as input and output amounts and for some processes also the types of inputs and outputs.

Table 12. Showing categorization of process steps used for the LCIA result for the engine

Remanufacturing Process Group	Specific process step
Internal Transportation	Crane
	Forklift
Inspection and testing	Testing Crankshaft
	Crack detection Testing Cylinder head
	Testing, full engine
	Controlling and Inspection Crankshaft
	Testing EGR cooler
	Drying EGR cooler
Washing	Pre cleaning, full engine
	Final washing, Cylinder block and Cylinder head
	Middle washing, Cylinder block and Cylinder head
	Alka jet washing
	FR washing
	Tunnel washing
	Tunnel washer blowdrying
	Parts washing
	EGR washing
Machining and special repair	Controlling and inspecting, full engine
	Machining, Cylinder head and Cylinder block
	Controlling and inspecting Cylinder head

	Polishing Camshaft
	Machining Cylinder head
	Machining Connecting rod
	Machining Crankshaft
	Machining Other
	Special repair
Blasting and burning	Blasting
	Burning
Assembly and disassembly	Disassembly, full engine
	Assembly, full engine
	Cylinder head disassembly
	Short block disassembly
	Valve seat removal Cylinder head
	Disassembly Connecting rod
Other	Painting
	Extra materials/auxiliary

Table 13 below shows the Remanufacturing Processes for the remanufacturing process group Testing. Some of the tests are confidential.

Table 13. Remanufacturing Processes in the remanufacturing process group Testing for the engine

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset

Testing Crankshaft	Input	Electricity		kWh	Estimated by Volvo Group employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
		Confidential				
Crack detection testing Cylinder head	Input	Electricity		kWh	Estimated by Volvo Group employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
		Confidential				
Testing full engine	Input	Diesel production and combustion			Estimated by Volvo Group employee	market for diesel, burned in agricultural machinery diesel, burned in agricultural machinery Cutoff, U - GLO
Controlling and Inspection Crankshaft	Input	Electricity		kWh	Estimated by Volvo Group Employee and operators	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
		Compressed air		m3	Estimated by Volvo Group Employee and operators	market for compressed air, 700 kPa gauge compressed air, 700 kPa gauge Cutoff, U - RER
Testing EGR cooler		Confidential				
Drying EGR cooler		Electricity		kWh	Estimated by Volvo Group Employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE

The only processes that are mapped in the remanufacturing of the engine that is not included in the LCA is the packaging, as this is outside of the scope of the study.

6.4.2 LCIA - Engine

The following section presents the LCIA results for the engine. The results are presented in the categories Transportation, Remanufacturing Processes and Material Exchange, for the impact categories chosen in Table 2. First, the total impact of the engine is presented, followed by a hotspot analysis for all three categories. After that, the sensitivity analysis is presented.

6.4.2.1. *Total Environmental Impact - Engine*

The total impacts of remanufacturing an engine are presented in Figure 19 below. The total numerical impact results are presented above each column, and the blocks in the column show each activity's percentual contribution in respective impact category. For example, the acidification impact for remanufacturing one engine reaches 12 mol H⁺-Eq.

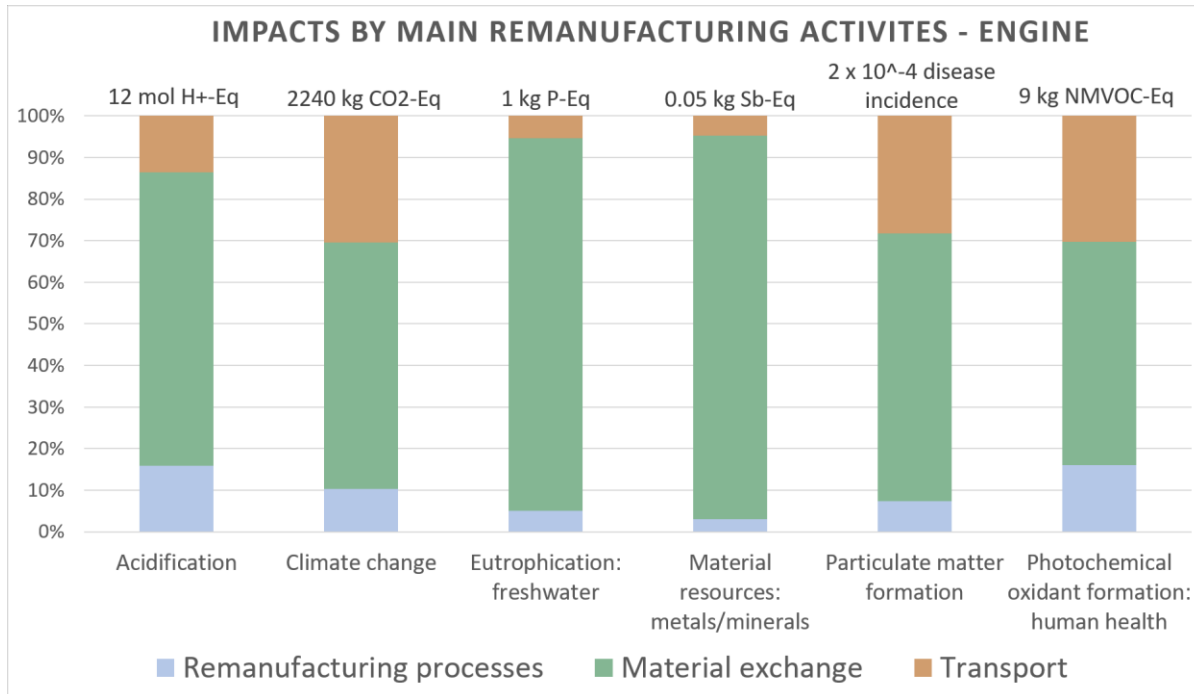


Figure 19. Impacts by the remanufacturing activities for the engine

It can be seen in the figure above that the Material Exchange is the largest contributor in all impacts categories. The contribution from Transport exceeds the contribution from the Remanufacturing Processes in the impact categories Climate Change, Material Resources: minerals/metals, Particulate matter formation and Photochemical Oxidant Formation: Human Health. In the impact category Acidification, the Remanufacturing processes contribute more than Transport, while the split between them is equal in the impact category Eutrophication: freshwater.

6.4.2.2. Hotspot Analysis- Engine

Based on the results in Figure 19 above, the Material Exchange is considered the largest hotspot in all impact categories. In each categories, the material impact stands for about 55 - 90% of the full impact in each impact category. Meanwhile, transportation represents approximately 5-30% and the Remanufacturing processes about 3-15%. As the Material Exchange is the greatest contributor in all impact categories, this will be examined first.

Thereafter, the second largest contributor, Transport, will be analyzed, and this is followed by the Remanufacturing Processes.

Hotspot Analysis of Material Exchange - Engine

In Figure 20 below, the environmental impact from the Material Exchange is split into each material's individual contribution to the impact.

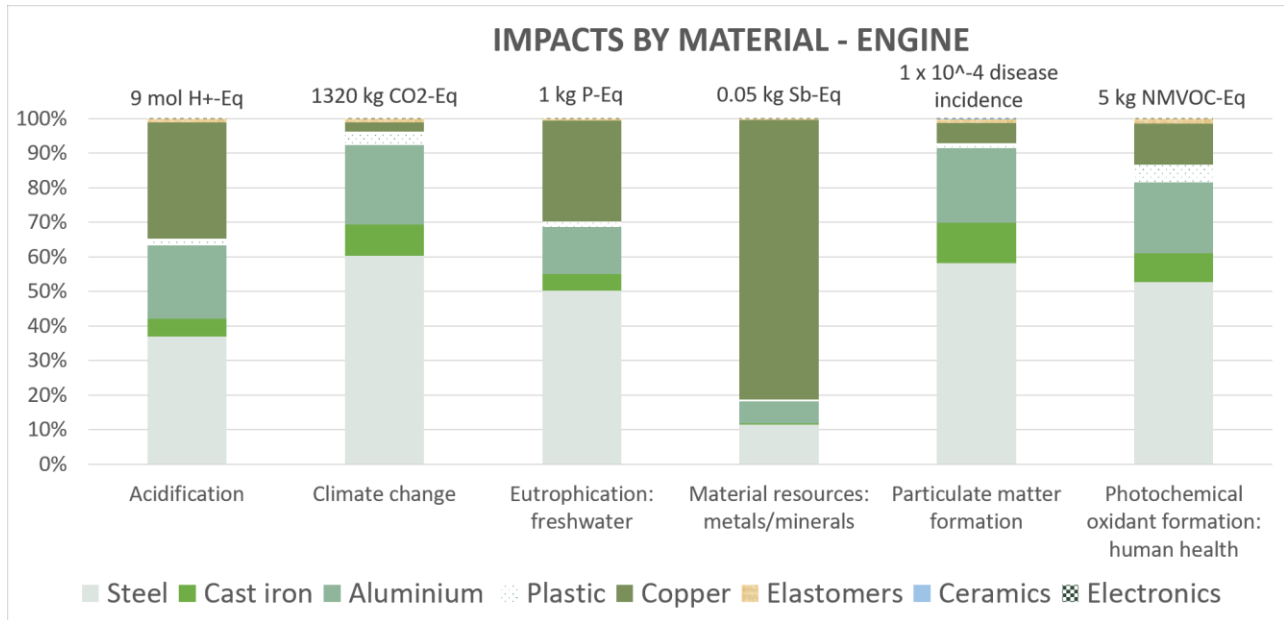


Figure 20. Hotspot analysis of Material Exchange, for the engine

It can be seen in the figure that for most impact categories, steel has the highest environmental impact, followed by aluminum and copper. In the impact category Material Resources: Minerals and Metals, copper has by far the highest contribution.

As the material impacts contributed to a large share of the total impacts from the remanufacturing of the engine, the impacts from each material and the total engine's impacts is presented in Figure 21a&b below, for the impact categories Climate Change and Material Resources: Minerals and Metals. The results for this split in all impact categories can be seen in Appendix C: Environmental Impact Results – Engine. The green sections represent material contributions, the orange sections represent transportation, and the blue sections represent remanufacturing processes.

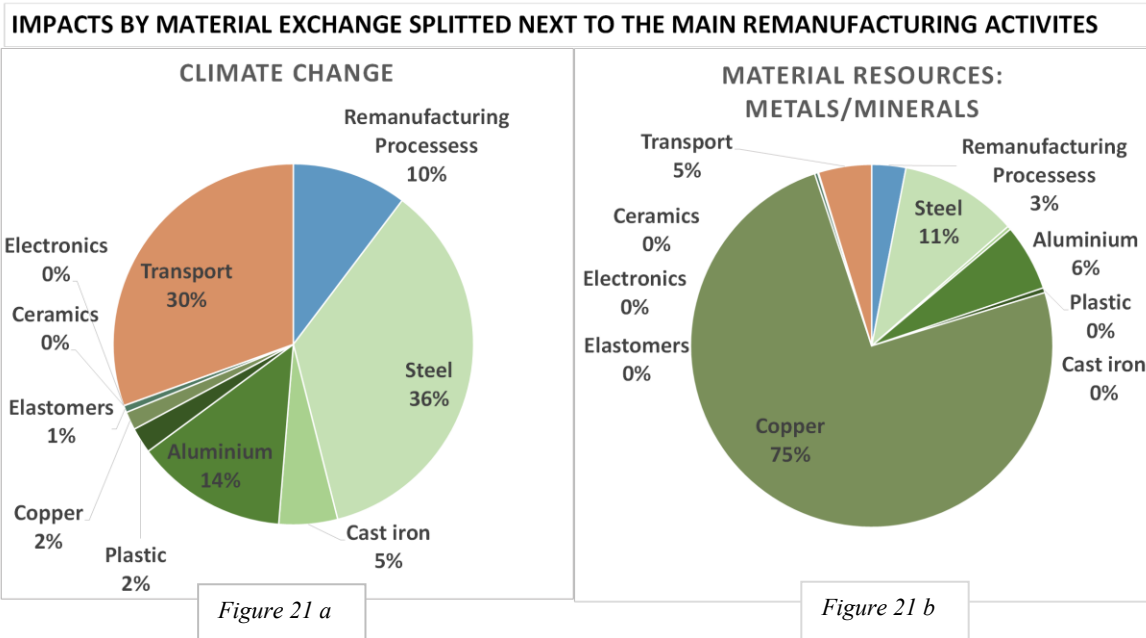


Figure 21a & b. Impacts by material categories split next to the main remanufacturing activities showing each material contribution to the full engine impact in Climate change and Material resources: metals/minerals impact categories.

It can be seen in the figure that in the category Climate Change, steel is a hotspot, followed by Transport. In the impact category Material Resources: Metals and Minerals, Copper is a hotspot, followed by Aluminum. In both impact categories, Aluminum contributes more to the impact than Remanufacturing Processes.

Hotspot Analysis of Transportation - Engine

The transportation is divided into Transportation of Material, Transportation of Core and Transportation to Recycling. The transportation is done by cargo ship or truck depending on the available transportation methods. The total impact from Transportation together with a split for each Transport group, is visible in Figure 22 below.

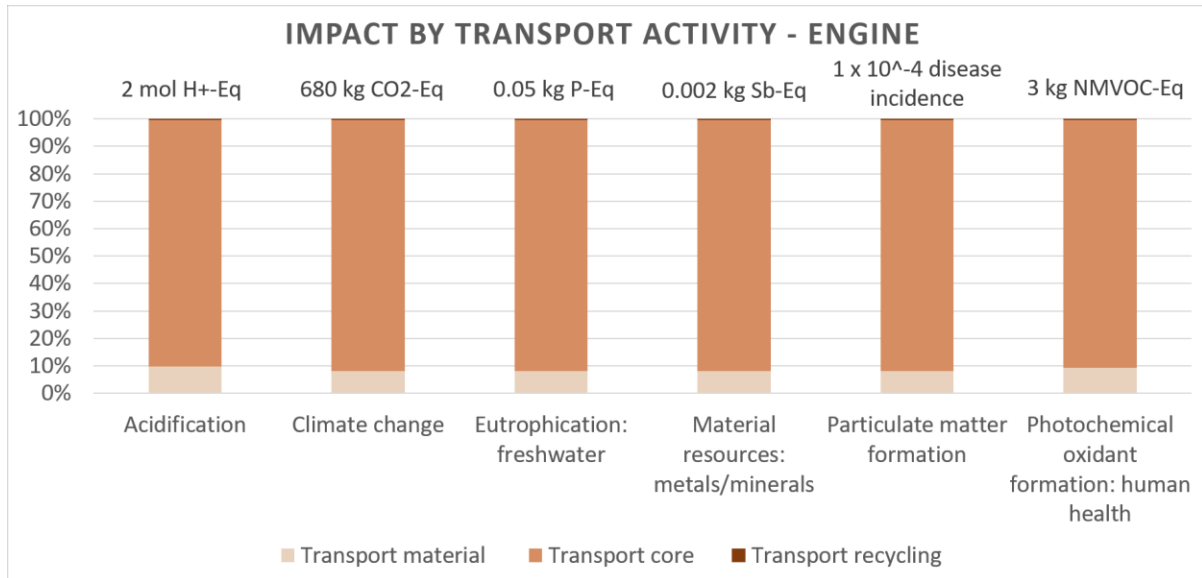


Figure 22. Hotspot analysis of transportation for the engine

The transportation of core is the largest contributor, with 91-92% of the total impact in each category. Meanwhile, the material transportation represents 8% of the emissions in each impact. The transportation to the recycling site stands for 0-1%, making it barely visible in Figure 22 above. It should also be noted that the weight of the engine weighs more than the new added material, and the transportation distance for the core is longer.

Figure 23 below shows the Transport of Core divided into the two transportation modes, Transport by truck and transport by ship.

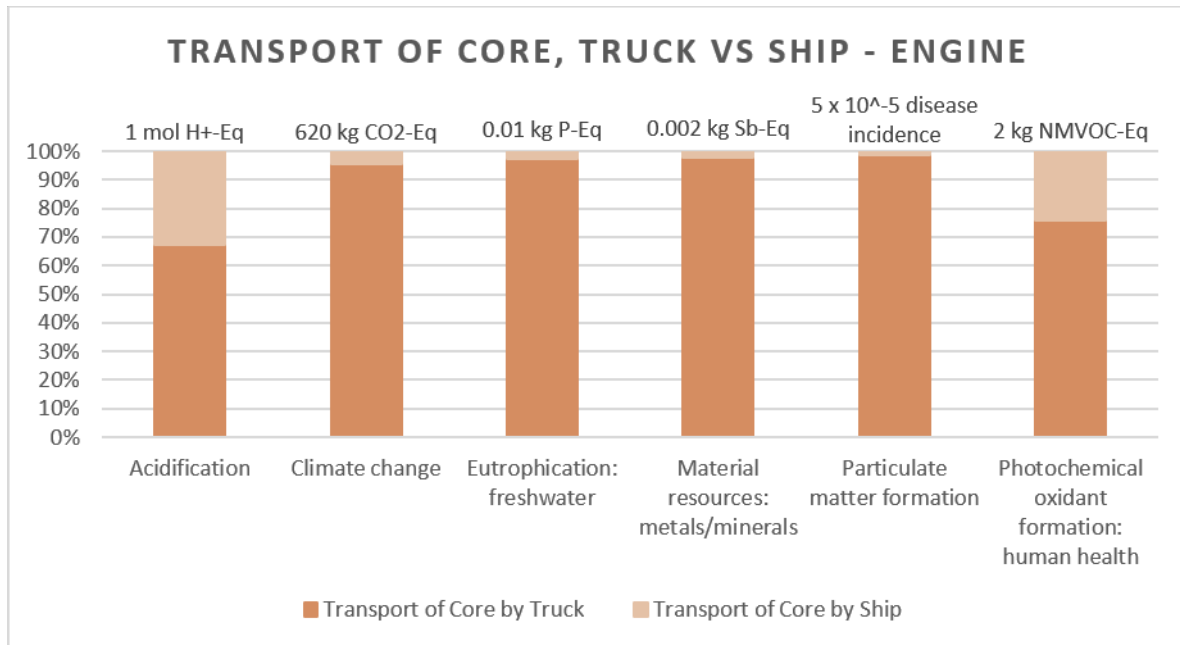


Figure 23. Hotspot analysis of Core transport split between truck and ship transport, for climate change impact category for the engine

The figure above shows that the Transport of Core by Truck is dominating Transport of Core in all impact categories. It should be noted that the core transportation by truck accounts for a larger share of the core transportation compared to the core transportation by ship, as most transportation of the core transportation is within Europe.

As the core transportation is the dominating contributor within the transportation impacts, and the transportation's impact on the full remanufacturing is notable, the relation of core transport to the full environmental impact of engine is interesting. In Figure 24a&b below, the different transportation categories are presented next to the Main Remanufacturing Activates: Material Exchange and Remanufacturing Processes, in the impact categories Climate Change and Material Resources: Metals/Minerals.

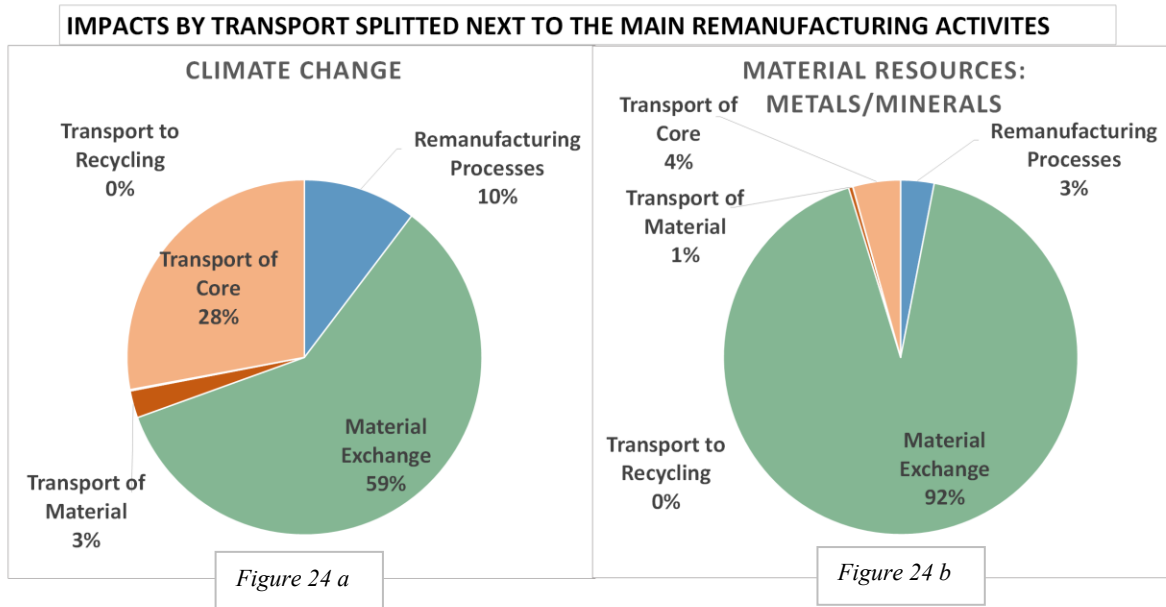


Figure 24a&b. Impacts by Transportation categories split next to the main remanufacturing activities showing each transportation contribution to the full engine impact in Climate Change and Material resources: metals/minerals impact categories

In the figure above, it is visible that for the impact category Climate Change, the transport of the core accounts for 28%, exceeding the impact of the Remanufacturing Processes. Meanwhile, in the impact category Material Resources: Metals/Minerals, the Transport of the core is lower, although still exceeding the impact from the Remanufacturing Processes.

While the impact for the transportation has a substantial share of the total CO₂-Eq emissions, the available datasets used to model it is not fully representative for the actual transportation. This will be further analyzed in a sensitivity analysis of the engine.

Hotspot Analysis of Remanufacturing Processes - Engine

Although the Remanufacturing Processes account for a small share of the total environmental impact across all impact categories, it could be one where Volvo Group has a big opportunity to influence the impact. Hence, the hotspot analysis of the Remanufacturing Processes is presented below, despite it having a low impact compared to the Material Exchange and Transportation.

The Remanufacturing Processes are divided into seven groups, as mentioned before. These are Internal Transportation, Inspection and testing, Washing, Machining and special repair, Blasting and Burning, Assembly and disassembly and other. The hotspot analysis of these groups is presented in Figure 25.

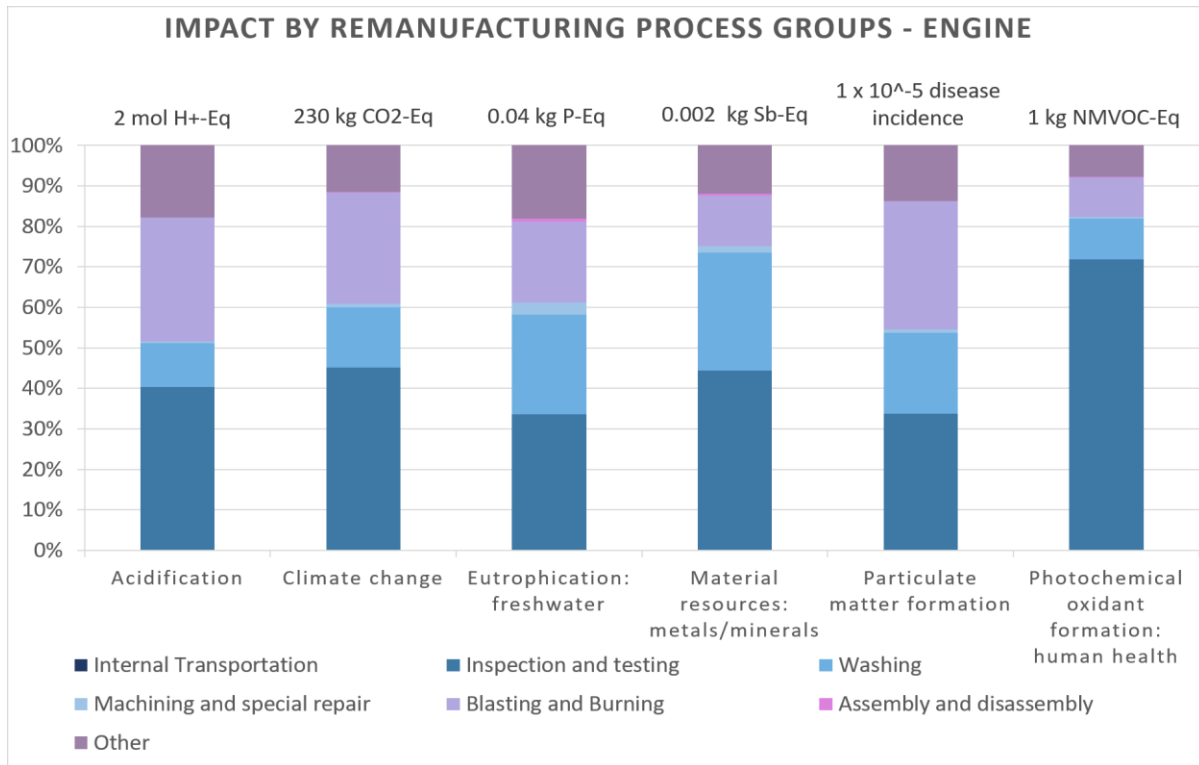


Figure 25. Hotspot analysis of Remanufacturing Processes for the engine

In each impact category, the Inspection and Testing processes contribute to the largest individual share, although marginally for the Particulate matter formation. Meanwhile, the Blasting and Burning, Washing processes as well as Other also stand for a large share in some impact categories. Hence, the four of them will be presented in more detail below.

The Inspection and Testing process group consists of six different kinds of tests and quality assessment processes. However, within these, the testing of the engine, at the end of the reassembly, stands for more than 99% of the full impact. The test burns diesel as the engine runs under various conditions. Since it contributes to 99% of the impact in the remanufacturing process group Inspection and testing, no figure of this is shown.

In the Figure 26 below, the environmental impact of the processes in the remanufacturing Process group Blasting and Burning are shown.

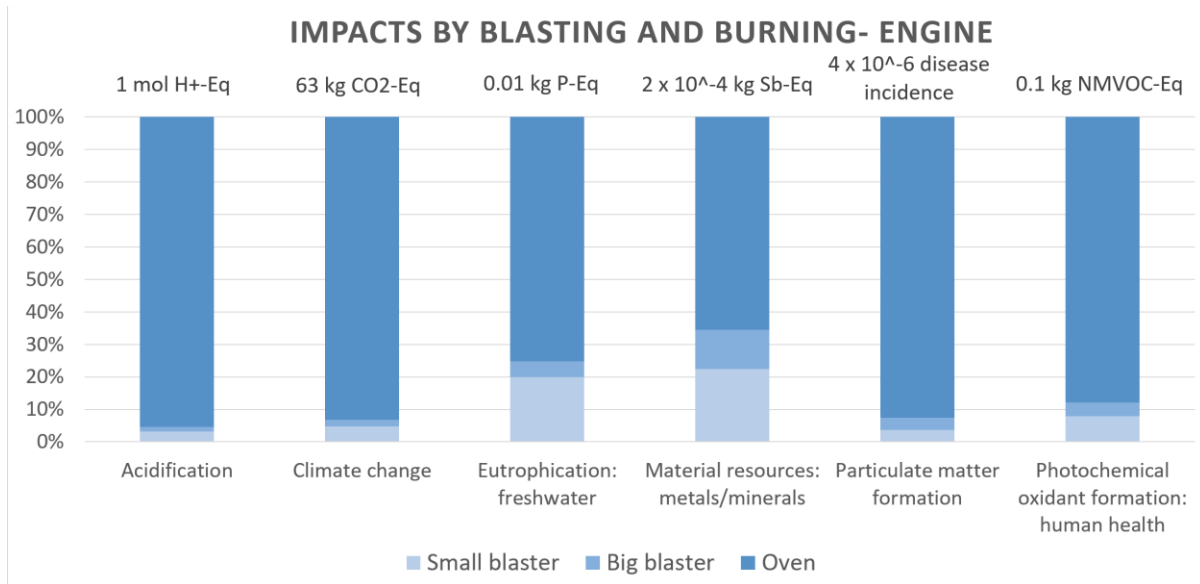


Figure 26. Hotspot analysis of Blasting and Burning remanufacturing processes for the engine

It is visible in the figure that the oven contributes to the largest share in all impact categories. In the impact category Climate Change, the oven accounts for 84% of the Climate Change impact, compared to the blasting processes contributing to the other 16%.

In the Figure 27 below, the impact of the Remanufacturing Process group Other is shown.

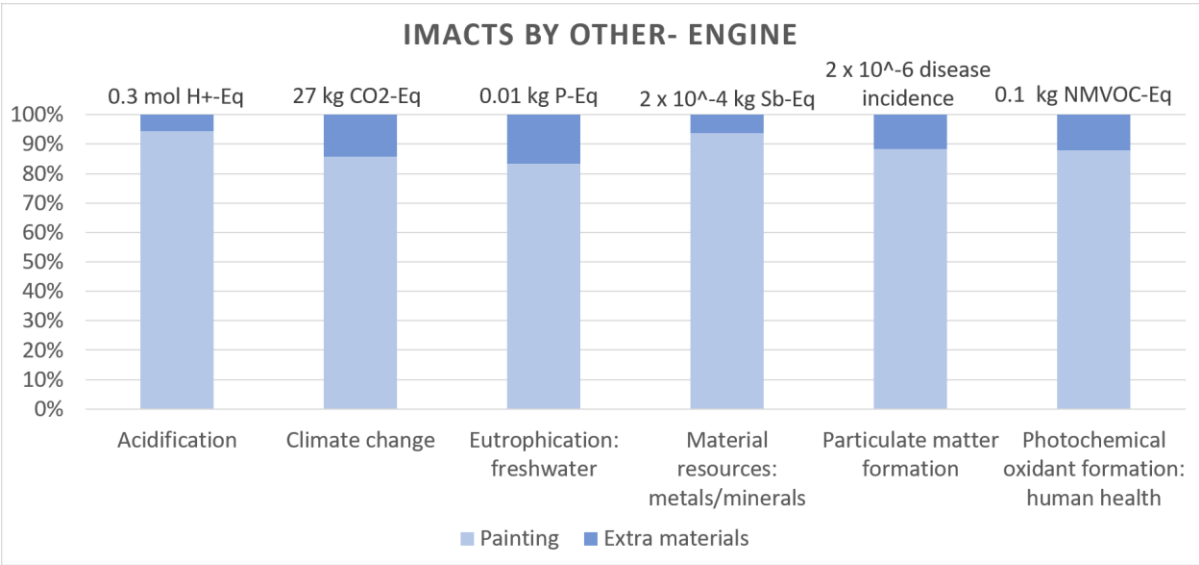


Figure 27. Hotspot analysis of the remanufacturing processes category Others, for the engine

It is visible in the figure that the painting is the dominating contributor, while the extra material is considerably lower. The distribution is relatively similar between the impact categories, indicating that the environmental burden from Painting is consistently high regardless of impact category.

In Figure 28 below, the contribution for each remanufacturing process within the group Washing is shown.

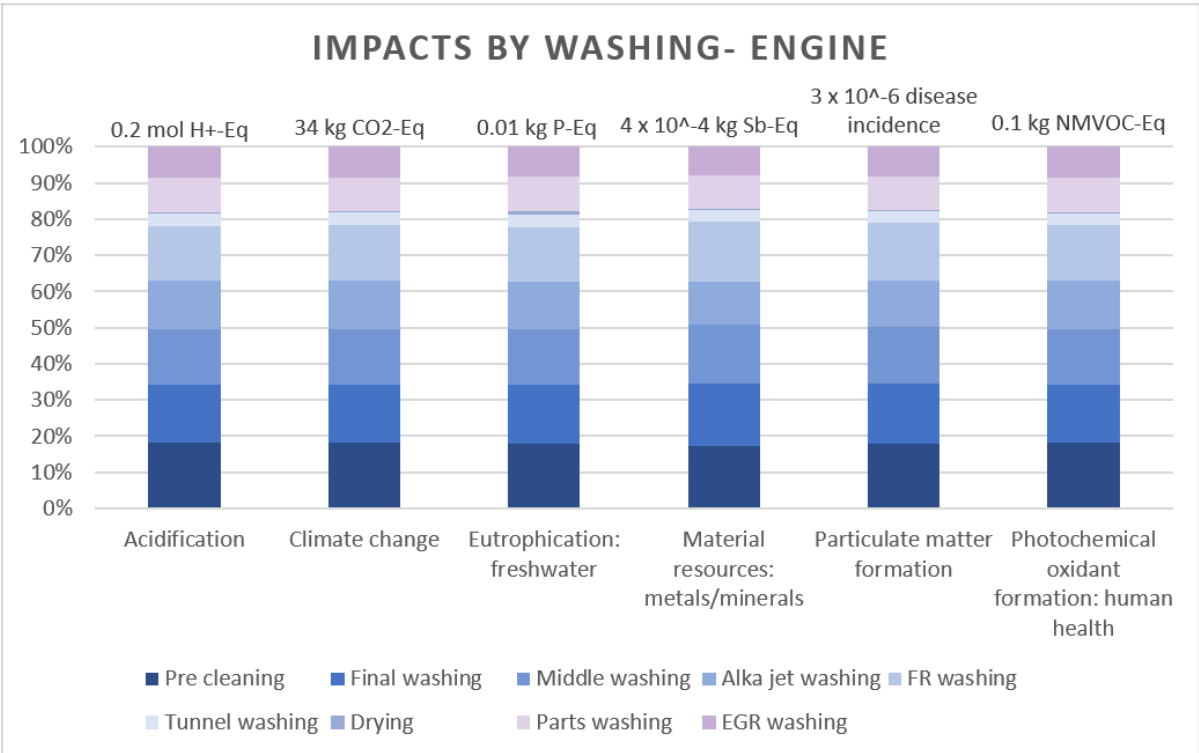


Figure 28. Hotspot analysis of the remanufacturing process category Washing for the engine

As can be seen above, the burden within the Washing processes are relatively evenly distributed over the nine washing machines. The largest percentual contribution, generated by the precleaning washing, contributes to 17-18% of the total impacts from washing in all impact categories.

6.4.3 Sensitivity Analysis- Engine

As shown in Figure 19 (total impact for the engine), the largest contributors to the overall environmental impact are the Material Exchange and Transportation categories. These categories are therefore the primary focus of this sensitivity analysis. Furthermore, the sensitivity analysis of the transportation is a part of answering RQ4: *How sensitive are the climate impact results to assumptions regarding transportation?*

In addition, the datasets used to model Material Exchange are uncertain, particularly regarding if the recycled material content in the material production datasets represent actual

operating conditions. The sensitivity analysis is therefore also an evaluation of data quality and modelling assumptions on the results.

The sensitivity analysis of the Material Exchange category is presented first, followed by the analysis of Transportation.

6.4.3.1. Sensitivity Analysis on Material Exchange –Engine

To evaluate the influence of material replacement on the environmental impacts of engine remanufacturing, a sensitivity analysis was conducted in which the environmental impacts associated with material exchange were reduced by 20%. The reduction was distributed equally across all included materials. Although a 20% reduction represents a substantial change, it illustrates the potential environmental improvements that could be achieved and highlights the possible importance of material-related impacts within the overall results.

Furthermore, such a reduction may not necessarily be unrealistic, even in the short term, considering the uncertainties associated with the material datasets used in the modelling. However, this may also contribute to a possible underestimation in environmental impacts. In particular, the datasets used may contain lower or higher shares of recycled material and emission factors than those representing the actual materials used in practice. When modelling the new materials, average manufacturing processes were added to some of the materials when necessary, based on discussion with a Volvo Group LCA practitioner. These are also uncertain, as they represent average processes. Consequently, the assumed reduction or increase in impacts can also be interpreted as a reflection of uncertainties related to the material modelling.

Due to the uncertainties in the datasets, an additional sensitivity scenario was also modelled, assuming a 20% increase in the environmental impacts associated with material exchange. This scenario was included to evaluate how variations in assumptions regarding Material Exchange influence the overall remanufacturing impacts. In both scenarios, the Transportation and Remanufacturing Processes categories were kept constant, corresponding to the modelling assumptions used in the main LCA results.

The result is visible in Figure 29 below, where the scenarios with the 20% increase and 20% decrease in impact from Material Exchange are modelled together with the Current scenario, used in the main result.

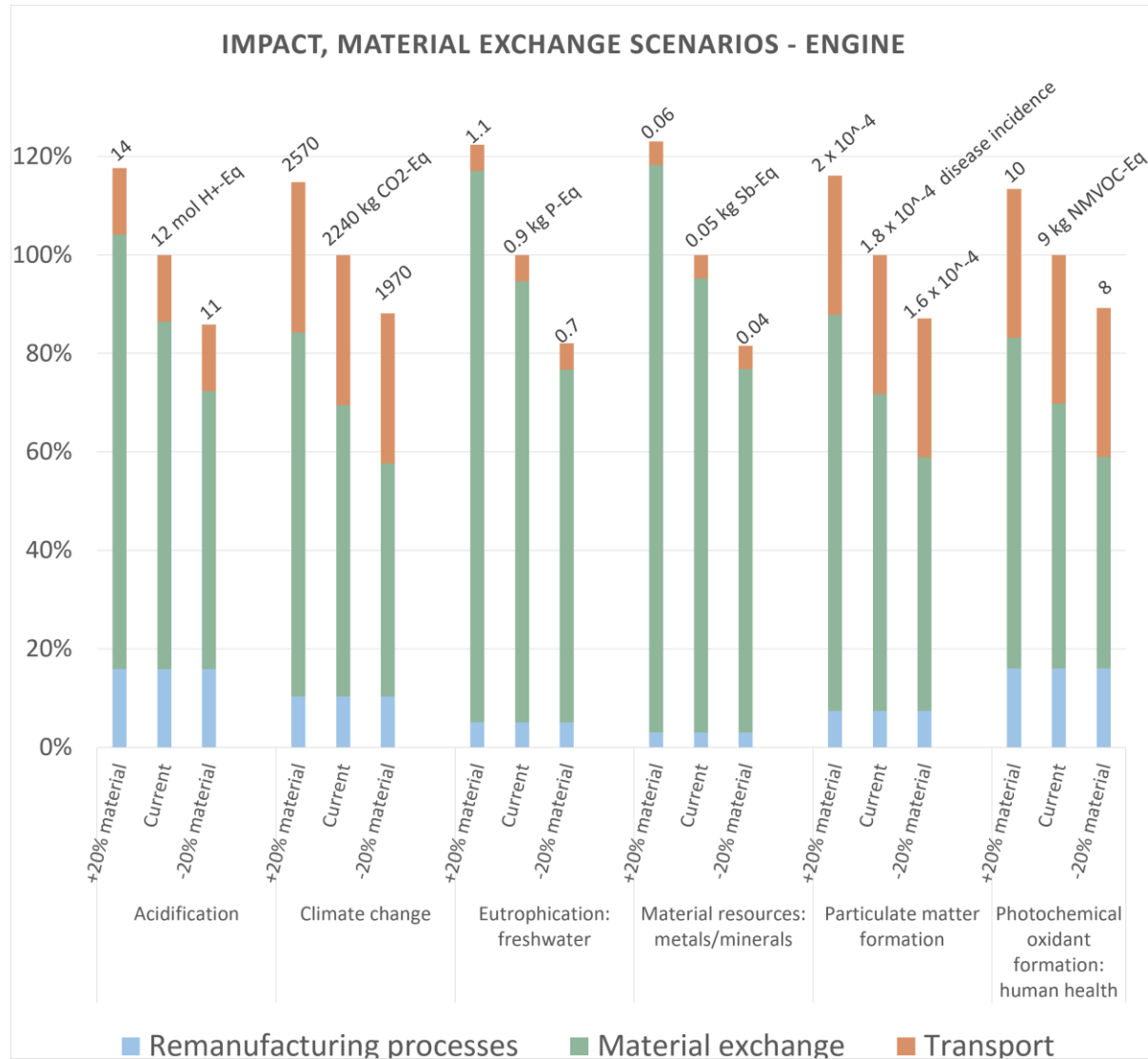


Figure 29. Sensitivity analysis of changes in material environmental impact for the engine

As shown in the figure above, the 20% reduction in material-related impacts resulted in the largest relative reductions for Eutrophication (22%), Material Resources: Metals/Minerals (20%), and Climate Change impacts (12%). The figure also shows that Material Exchange remains the dominant contributor in most impact categories, even after the reduction scenario is applied.

6.4.3.2. Sensitivity Analysis of Transportation – Engine

The sensitivity analysis of transportation for the engine contains two parts. The first part follows the same methodology as presented for the DPF, with varying the load factors used in the transportation modelling, and comparing that to the Current Scenario in the main results shown in Figure 19. The second part focuses on an additional case where the core transport done by truck is fully electric. This scenario is included to evaluate the potential influence of alternative transportation technologies on the overall environmental impacts. Only the transportation by truck is adjusted, while the transportation by ship is kept constant in all scenarios.

For the engine, the transportation is divided into Transport of Core, Transport to recycling and Transport of Material, the latter referring to transportation associated with added subcomponents. Similar to the DPF analysis, the scenarios are defined based on percentages of the maximum truck load capacity of 18 tons, using the same assumptions regarding load factors and empty return transports. However, unlike the DPF, the engine remanufacturing also includes transportation related to material exchange, which is therefore included in the analysis. The Transport of material is modelled in the same scenarios as the Transport to recycling, while the Transportation of core is varied separately.

The scenarios are named based on the scenarios plotted, with names of MRX/CY where MR stands for Material and Recycling transportation and X is the load factor used for that transport, and C represents Core transportation and Y the load factor for the corresponding transport. In the first scenario, MR50/C32, the Material and Recycling transportation reaches a 50% load factor, while the core transport is kept at 32%. The most optimal scenario is MR50/C100, meaning a scenario where the core transportation reaches a 100% load factor (18 tons), while Material and Recycling transport reach 50% (9 tons).

The scenarios are presented in Table 14 below. It is important to note that these figures represent modelling choices rather than the physical weight of specific components. They just serve as a proxy to adjust the environmental impact per ton-kilometer in the LCA.

Table 14. Scenarios used in the sensitivity analysis for the engine transportation

Scenario / type of transport	Current scenario	MR50/C32	MR32/C50	MR50/C50	MR50/C75	MR50/C100
Material and recycling transport	32% 5.79 ton	50 % 9 ton	32% 5.79 ton	50 % 9 ton	50 % 9 ton	50 % 9 ton
Core transport	32% 5.79 ton	32% 5.79 ton	50% 9 ton	50% 9 ton	75% 13.5 ton	100% 18 ton

The load factors in the table above were used and resulted in the Figure 30 below, showing the Climate Change impact for the different scenarios, split between Transport to recycling, Transport of material, and Transport of core.

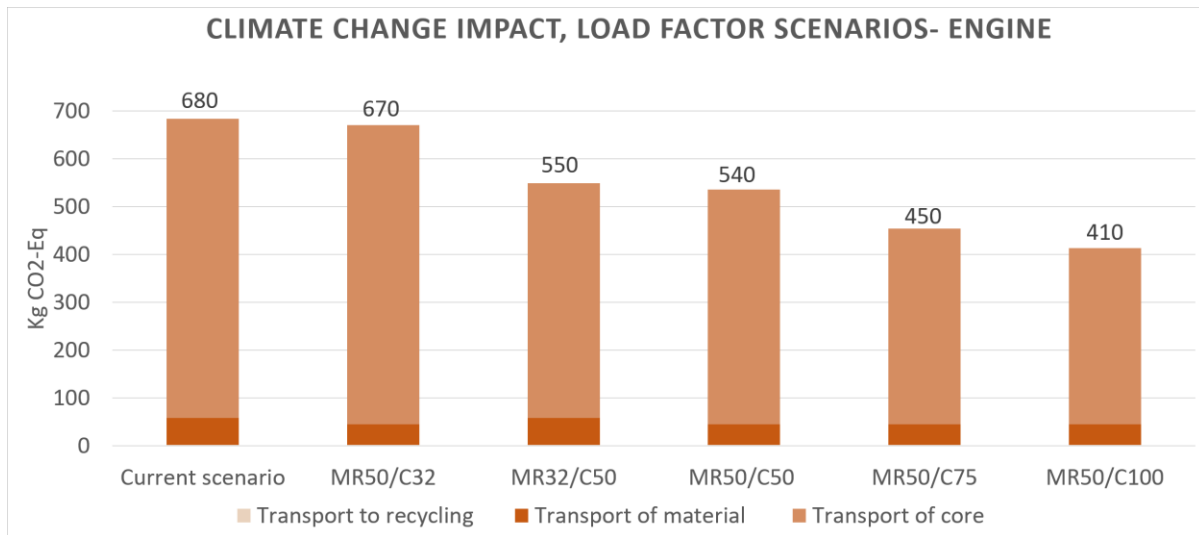


Figure 30. Sensitivity analysis of different transportation scenarios, using load factor, measured in Climate Change impact category for the engine

From the analysis, the utilization of available freight capacity can play an important role in reducing environmental impact, as the MR50/C100 scenario decreases the Climate Change impact from transportation by 40%. Comparing scenarios MR50/C32 and MR32/C50 shows

that optimizing core transportation provides a larger environmental benefit than optimizing material and recycling transport. Increasing the load factor to 50% for material and recycling transport reduces the impact by 2%. In contrast, when the load factor for core transportation is increased to 50%, while material and recycling transport is kept at 32%, the impact is reduced by 20%.

The additional sensitivity scenario is conducted below, in which the core transportation done by truck is assumed to be fully electric. The core transport that is done by ship, the Transport of Material and Transport of core are not changed. In this analysis, both an European and Swedish electricity mix has been used.

Meanwhile, for the modelling of the electric transport, no dedicated dataset for electric freight transport was available in the database used (Ecoinvent 3.12). The electric truck transport was instead modelled based on an assumption about the electricity consumption per km. The modelling assumes a load corresponding to the default transport dataset, i.e., a load of 5.79 tons. As the engine represents approximately 20% of this load, only 20% of the electricity consumption was allocated to the engine. Furthermore, the modelling only includes the electricity consumption of the truck and does not account for other transport-related impacts such as road wear, infrastructure use, tire wear, brake emissions, or vehicle manufacturing. Consequently, the results should be interpreted with these limitations in mind. This will be further discussed in the following discussion chapter.

The scenarios below are labelled MR32/C-electric (RER), meaning Material and Recycling transport with 32% load factor and an electric truck core transport using European electricity mix, and MR32/C-electric (SE), modeling the same scenario but with a Swedish electricity

mix. The result for these scenarios on Climate Change impact is visible next to the Current scenario in Figure 31 below.

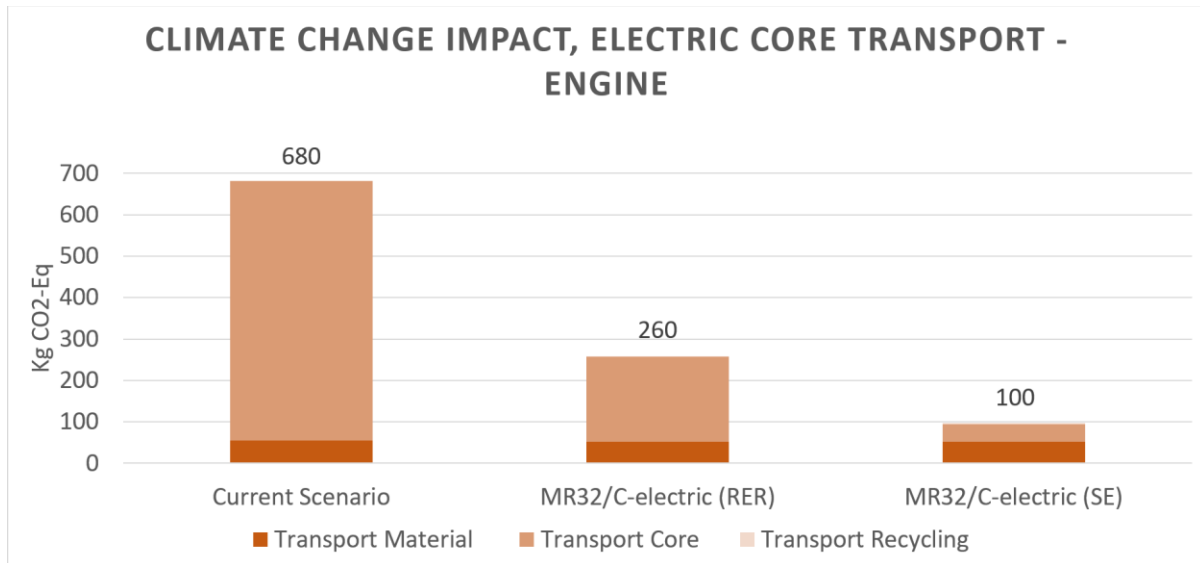


Figure 31. Sensitivity analysis of different transportation scenarios, using alternative fuels, measured in Climate Change impact category for the engine

The result shows that a core transportation with an electric truck decreases the impact by 62% if a European electricity mix is applied, and by 86% if a Swedish electricity mix is used. However, as previously mentioned, these results should be interpreted with caution, as the modelling of electric transportation was simplified due to data limitations.

6.4.3.3. Sensitivity Analysis, Combined Scenarios- Engine

In this section, the sensitivity scenarios related to Material Exchange and Transportation are combined to evaluate how they affect the total environmental impact from remanufacturing of the engine.

In the first scenario (MR50/C100 and reduced material exchange), the Transportation of Material and Transportation to Recycling are modelled with a 50% load factor, while the Core Transportation is assumed to operate with a 100% load factor (MR50/C100). In addition, the environmental impact from Material Exchange is reduced by 20%.

The second scenario (MR50/C-electric (RER) and reduced material exchange) uses the same assumptions for load factors and reduced Material Exchange impacts but assumes that the Core Transportation is carried out using electric trucks with a European electricity mix.

The third scenario (MR50/C-electric (SE) and reduced material exchange) is modelled in the same way as the second scenario but instead uses a Swedish electricity mix for the electric Core Transportation.

The impacts from these scenarios are presented next to the Current Scenario. The results are shown in Figure 32 below for the impact category Climate Change, and are divided into contributions from Remanufacturing processes, Material impact, and Transportation.

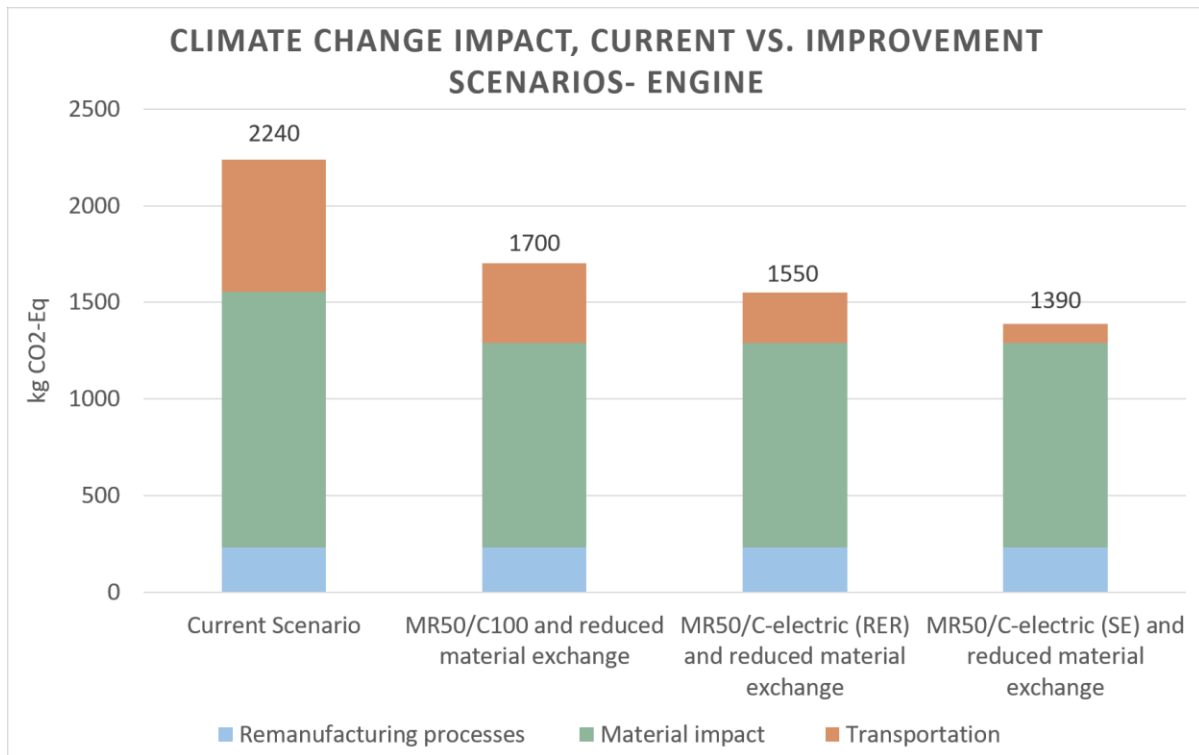


Figure 32. Sensitivity analysis of the combined scenarios of materials exchange and transportation, measured in the climate change impact category for the engine

The results of these combined scenarios show that when the Current Scenario is compared to the scenario MR50/C100 and reduced material exchange, the Climate Change impact is decreased by 24%. When this is combined with an electric truck core transportation with a European electricity mix, the impact is decreased by 30% compared to the Current Scenario.

When a Swedish electricity mix is used instead, the Climate Change impact is decreased by 38% compared to the Current Scenario.

7. Discussion

The following chapter discusses the results and analyses to provide recommendations for possible improvements and future research. It will also treat the credibility of the results and its limitations.

7.1. Discussion of the MFA Results

The semi-quantitative MFA supported in the understanding of the component flows within the remanufacturing and refurbishment sites, and the documentation is an important aspect of that. In this section, the results of the semi-quantitative MFA are discussed.

7.1.1 Circular Process Complexity

The semi-quantitative MFAs of the DPF, engine, and battery display a broad range of remanufacturing processes. The DPF has a less variation in remanufacturing processes, consisting mainly of cleaning and testing to ensure proper functionality. In contrast, the remanufacturing of the engine is more complex in terms of the number and variation of process steps, component flows, material exchanges, and machining carried out.

For the battery, the MFA flow chart looks rather simple. There is a limited amount of process steps and the flows are not separated much. However, the complexity of the battery refurbishment lies within safety requirements, as the operator works with electrical components. Furthermore, the cleanliness regulations add even more complexity and demands on the facility, as cleanrooms are needed.

The three MFAs showcase very different remanufacturing and refurbishment strategies, and the components have a very different character. This highlights the wide range of remanufacturing possibilities that exist within the automotive industry, and how both complex components with thousands of subcomponents can be remanufactured, as well as simpler assemblies.

7.1.2 Material Saving and Material Exchange

While circular activities aim to close material loops and avoid the extraction of new resources, the semi-quantitative MFA reveals that material exchange can be a part of remanufacturing. However, the need for new material varies greatly depending on the component. As seen in the remanufacturing of the DPF, no new material is added through material exchange. On the other hand, for more complex components like the engine and battery, material exchange plays a crucial role in restoring worn-out subcomponents, and this enable the reuse of the remaining original parts.

In other words, introducing an amount of new material can act as an enabler to save a much larger share of old material. However, as the LCA results demonstrate, the production of these new replacement parts has a substantial environmental impact.

To fully capture these trade-offs, the semi-quantitative MFA provided an important groundwork for the environmental assessment, as it enabled the identification of remanufacturing processes, subcomponents flows, waste, and transportation requirements. Ultimately, combining MFA and LCA provides a solid basis for understanding these circular processes, while simultaneously evaluating their environmental impact. This environmental contribution is discussed further in the following section.

7.2. Discussion of Environmental Impacts

The results of the environmental assessments of the DPF and engine will be briefly discussed in the following section. This will be followed by a deeper discussion regarding the material and transport impact in section 7.3 and 7.4, respectively.

7.2.1 DPF Remanufacturing

For the remanufacturing of the DPF, transportation was the dominant contributor to almost every impact category considered, which can be explained by two main factors. Firstly, the

DPF remanufacturing has a low material replacement rate, meaning very little new material is added. Secondly, the impact of the remanufacturing processes is relatively low. Consequently, transportation has become the most prominent factor. This indicates that when the factory footprint is lower, the logistics of transportation become the critical determining factor for the overall sustainability of the system.

7.2.2 Engine Remanufacturing

The environmental impact of the engine remanufacturing is strongly tied to the new material added. Materials account for 59% of the total climate change impact, and even larger shares in most of the other impact categories. Despite not replacing the full engine, the replacement of material, and especially environmentally intensive metals, can still have a high environmental impact.

As seen in the material contribution breakdown in Table 11, the specific contribution varies a lot depending on the impact category considered. For example, steel contributes to 36% of the full remanufacturing impact in the impact category Climate Change, and as seen in Table 11 it stands for 60% of the total weight of the replaced material. It also accounts for 11% of the impact in the impact category Material Resources: Metals/Minerals. Meanwhile, copper only contributes to 2% in the impact category Climate Change but dominates in the Material Resources: Metals/Minerals category, standing for 75% of the total impact of remanufacturing a full engine. Considering this impact category, recycling of copper is of importance. Simultaneously, copper only accounts for 2% of the total weight of the new material.

Furthermore, these variations demonstrate that the environmental performance of a remanufactured engine depends heavily on which impact category is in focus. However, when looking at the overall environmental impact, it is obvious that material production is the primary driver of all environmental impact categories in the study. This underscores that material efficiency, such as maximizing the use of original components rather than introducing new materials within remanufacturing, is an important factor to improve the

sustainability of the system. A more detailed discussion on material impacts in remanufacturing and refurbishment is carried out in the following section.

7.3. Material Exchange Contribution

As mentioned above, Material Exchange contributes largely to the total environmental impact of the engine remanufacturing. Even though remanufacturing avoids the production of an entirely new engine, the environmental impact associated with producing the replacement materials is still a large share of the environmental impact. This aligns with the study by Zheng et al. (2019) mentioned in section 2.2 Previous Studies and Literature, that states that the production of new replacement components has a large impact, and contributes more to environmental impacts than the restoring operations.

At the same time, the remanufacturing process saves a large share of the original engine material. Although certain components and materials need to be replaced to restore functionality and quality, the majority of the engine's material weight and components are saved, which is one of the fundamental ideas behind remanufacturing.

The results therefore indicate that the environmental performance of remanufacturing depends strongly on the amount of material that needs to be replaced. If replacement rates become too high, the environmental benefits of remanufacturing decrease. On the other hand, replacing selected worn components can extend the lifetime of the overall product and enable continued reuse of the remaining material and components.

The large contribution from Material Exchange also highlights the importance of design for easy remanufacturing. This area has not been examined in this study. However, when designing components with the purpose of that it will be remanufactured, one could for example design component so that it is easily disassembled and so that a functional subcomponent are not scrapped when attached to a subcomponent that has to be scrapped. The importance of applying this in development phases of products has been highlighted during discussions with Volvo Group employees as something they have worked on to

improve the circularity of their products. Furthermore, investigating which subcomponents that must always be replaced according to technical requirements and why, and making efforts to decrease these amounts, could decrease the Material Exchange and therefore the environmental impact. Additionally, components designed to withstand wear for longer periods could reduce the Material Exchange, and therefore reduce the environmental impacts associated with remanufacturing. However, the reconstruction of a component to withstand more wear may also increase material use in the original production or increase environmental impacts in other ways during production.

Another aspect is the timing of remanufacturing. Components need to be remanufactured early enough to avoid wear that reduces the opportunity of recovery of the component. At the same time, performing remanufacturing too early could possibly lead to unnecessary material replacement and additional environmental impacts, since some subcomponents must always be replaced, even though they may still have remaining useful life. This suggests that there could be a balance regarding when remanufacturing should be carried out in order to maximize material reuse.

7.4. Transportation in Circular Systems

The results from both the DPF and engine remanufacturing show that transportation can contribute greatly to the total environmental impact of remanufacturing of these components. This aligns with previous findings presented in section 2.2. Previous Studies and Literature, where transportation is mentioned as a factor that can increase the environmental impact of remanufacturing (OECD, 2019), due to the need for collecting and transporting cores over potentially long distances (Ullah, 2023).

Circular systems are not automatically environmentally beneficial. One aspect of this is transportation, where the environmental benefits can partly be offset by transportation in regards to the load factor and energy source used for the truck. Increasing the load factor could be one strategy for reducing the environmental impacts associated with remanufacturing. The analysis of electric truck transportation also indicates a large reduction

for Climate Change impacts. However, these results should be interpreted with caution due to the simplified modelling assumptions because of limitations in the available datasets.

Nevertheless, if freight transportation becomes less carbon-intensive in the future, and the load factor increases, the environmental performance of remanufacturing could be improved.

In addition, early inspection or assessment of returned cores at regional hubs could potentially reduce unnecessary transportation of components that are unsuitable for remanufacturing, therefore lowering the impacts from transportation. However, early assessments could be more challenging for complex components with many subcomponents, such as engines. In these cases, the component may need to be partly disassembled before it is possible to determine which subcomponents can be reused. In contrast, an initial assessment of the DPF, which is a less complex component, could potentially be carried out more directly through for example visual inspection.

Overall, the findings highlight that transportation and logistics should be considered important aspects when evaluating the environmental impact of remanufacturing.

7.5. Discussion of Remanufacturing Processes

In this section, the environmental impact of the Remanufacturing Processes is discussed, first for the DPF and then for the engine.

7.5.1 Remanufacturing Processes - DPF

For the DPF remanufacturing, the Cleaning and Protecting Surface processes dominated the environmental impacts within the Remanufacturing Processes. The results indicate that Cleaning and Protecting Surfaces could become important environmental hotspots in remanufacturing systems where little material exchange occurs. Although the DPF remanufacturing avoids large material impacts, energy and resources are still required to restore the component's functionality. In addition, the cleaning processes generate hazardous waste that needs further treatment, contributing to additional environmental burdens.

At the same time, these cleaning processes are also what enable the reuse of the original DPF, since the removal of soot and ash makes it possible to restore the component without replacing material. As mentioned earlier in the literature review, Yoshimura et al. (2024) found that the environmental impacts of DPFs in construction machinery were mainly driven by raw material production and manufacturing of new filters, and that remanufactured DPFs could reduce global warming potential by 47%. Although the scope and system boundaries differ from the present study, these findings provide context for understanding the environmental importance of remanufacturing.

Despite this, the environmental impacts associated with the cleaning could possibly be reduced if the cleaning technology becomes more efficient. In addition, if the electricity mix used in the remanufacturing processes becomes less carbon-intensive in the future, the environmental impacts associated with the Remanufacturing Processes for the DPF would also decrease. On the other hand, if a less carbon-intensive electricity mix is also used in, for example, the material production, the relative environmental impact of remanufacturing might not decrease when set in a broader context.

7.5.2 Remanufacturing Processes- Engine

For the engine remanufacturing, the engine testing process accounted for the largest share of the impacts within the Remanufacturing Processes, caused by diesel combustion. Although testing contributes substantially to environmental impacts within the remanufacturing processes, this activity is done to ensure component functionality and reliability. Perhaps the duration of the engine test could be reduced or more optimized, but there is also a trade-off between environmental impact and quality assurance in remanufacturing of the engine.

The oven process was also identified as a hotspot within the Remanufacturing Processes. However, the oven used in the Burning process is operated using rapeseed methyl ester (RME), and the modelling of this process involved several assumptions and uncertainties, which are discussed further in section 7.6.3. Improvements could be for example if the oven process were instead fully electrified, the environmental impacts would likely decrease,

especially in regions such as Sweden with a low-carbon electricity mix. However, the feasibility of this has not been examined in this study, and the temperatures required in these processes are very high, meaning that large amounts of electricity would likely be needed.

Another relevant aspect when looking at the results of the Burning is that the Climate Change impact results in this study are presented within the impact category Climate Change total. According to the Environmental Footprint methodology (EF v3.1) used in the modelling, the Climate Change impact category can be divided into the three subcategories: Climate Change fossil, Climate Change biogenic, and Climate Change land use and land use change. Since the emissions from RME are not fossil, the results would appear differently if the category Climate Change fossil was considered separately. A separate assessment of the climate change subcategories could therefore provide a more representative understanding of the climate change impacts associated with the oven process.

7.6. Uncertainties of the Results

The results of this thesis are influenced by modelling assumptions, data availability, methodological choices, and simplifications necessary to model the systems. The following section discusses the most important methodological limitations and uncertainties related to the study. The semi-quantitative MFA mainly aimed to map process steps, component flows, and material exchanges within the remanufacturing systems, and therefore involved fewer quantitative assumptions than the environmental assessment. Consequently, the methodological discussion in this section mainly focuses on the LCA modelling and the uncertainties associated with the environmental impact assessment.

7.6.1 Data Quality and Primary Data Collection

The study combines both primary and secondary data. A large share of the remanufacturing process data was collected directly from Volvo Group, since data specific for the Remanufacturing Processes and associated transportation were needed.

Much of the inventory data relied on assumptions and estimates. For example, consumption of auxiliary materials such as oils, silicone, absorbents and other consumables was in several cases estimated together with operators. Although many of these flows contributed relatively little to the total environmental impacts, they still introduce uncertainty into the modelling.

A substantial share of the inventory data consisted of primary data collected through interviews, internal documentation, and operator estimations. Since many data providers did not have prior LCA knowledge, there was a risk of inconsistencies in data interpretation and reporting. To reduce this uncertainty, efforts were made to clearly define the requested information and continuously validate collected data. Furthermore, some primary data were collected on-site by colleagues, which limited the authors' control over the data collection process. This introduced additional uncertainty regarding data consistency and accuracy.

While considerable effort was spent on collecting detailed primary data for the remanufacturing activities, many upstream and background processes were modelled using generic datasets from Ecoinvent 3.12. These datasets can represent average global or regional production systems. Therefore, for example, the electricity mixes and production technologies in the datasets could differ from the actual conditions of the remanufacturing of the components in this study.

7.6.2 Modelling of the Material Exchange

In the remanufacturing of the engine, the Material Exchange contributed largely to the total environmental impacts, and it also includes some uncertainties. The material modelling was simplified by grouping materials into broader categories. This enabled the modelling to remain manageable, but more detailed and specific datasets could have an effect on the results.

The datasets used to model Material Exchange were chosen as the best approximations. However, several datasets used for manufacturing processes for material represent average material working operations. Discussions with an LCA practitioner connected to Volvo Group indicated that these generic manufacturing datasets can overestimate environmental impacts compared to the actual manufacturing processes used. In addition to this, the

recycled content in the material datasets used was not always known. In many cases the datasets represent average global production systems, and the actual materials used in practice can contain other shares of recycled material. The recycled content levels could not be adjusted within the modelling and therefore contributed to uncertainty in the results in the Material Exchange.

7.6.3 Transportation Modelling Assumptions

The transportation modelling includes several important assumptions and simplifications, since generic transport datasets from Ecoinvent 3.12 were used.

One important uncertainty relates to load factors, and a sensitivity analysis was conducted to evaluate the influence of different load factors. This showed that assumptions regarding this have a large effect on the result. No sensitivity analyses were performed on the core transportation done by ship, as it did not account for as large share of the impact from core transportation as the transport done by truck did.

The modelling of electric truck transportation introduces uncertainties. Since no dataset for electric truck transport was available in Ecoinvent 3.12, the electric transportation scenario was modelled only based on truck electricity consumption per kilometer. As a result, several impacts included in the diesel transport datasets, such as tire wear, brake wear, infrastructure use, and vehicle manufacturing, were not included in the electric transport modelling. This data asymmetry limits the comparability between the diesel and electric truck transportation. Furthermore, the electric truck transportation sensitivity analysis only considered Climate Change impact. Other impact categories, such as Material Resources, could potentially increase due to battery production and additional material requirements associated with electric vehicles. The results should therefore not be interpreted as a complete environmental comparison between diesel and electric transportation.

Some of the transport-related environmental impacts are currently aggregated into a single category called Transportation of Cores. However, this category combines two distinct transport phases, the movement of cores from national core hubs to renovator sites, and the transport of remanufactured components from those sites to the central distribution center.

Because these phases are grouped together, it is not possible to determine which of the two transport types contributes more to the overall environmental burden. Furthermore, this category bundles multiple specific transport legs, such as routing from a national core hub through the central distribution center to the renovator site. These results cannot be separated, which ultimately limits the ability to isolate and identify the environmental impact of each individual leg.

In the transport modelling, the transportation of the remanufactured component from the central distribution center to the dealer is not included due to lack of access to data. As the customers returning the core might not be the same wanting to buy a renovated spare part the corresponding data for these transportation legs could not be used. This part of the transportational modelling is hence expected to be an underestimation.

7.6.4 Modelling of Remanufacturing Processes

Several remanufacturing processes required simplified modelling approaches due to limited data availability and lack of representative datasets.

One example is the modelling of the oven processes used during engine remanufacturing. The ovens use RME as fuel, but there was no dataset for the combustion of RME in the database used. Instead, the amounts of emissions from combustion were estimated, based on energy content and emissions when burning diesel. This introduces uncertainties regarding the overall environmental impact of the oven. In addition, the amount of RME used was based on purchased quantities during 2025 together with assumptions regarding actual process consumption.

The modelling of detergents used in the washing processes for the remanufacturing of the engine also involved uncertainties. Due to limitations in available datasets, the same detergent dataset was used to represent several different detergents used within the remanufacturing system. Although the selected dataset was considered the most representative option, it is possible that the actual detergents differ in environmental impact.

For the DPF remanufacturing, the quantities of soot and ash removed during the cleaning processes were uncertain and based on estimates. This uncertainty motivated the sensitivity analysis conducted for waste quantities, which showed that variations in waste assumptions had a rather low influence on the total environmental impacts.

One limitation of the result of the remanufacturing of the engine is that when a subcomponent of a core cannot be reused and is replaced by a remanufactured equivalent spare part originating from another core, no environmental impact was accounted for the remanufacturing of the added spare part. This contributes to underestimations in the environmental impact of the remanufacturing process of the engine.

7.7. Implications for Circular Economy

In contrast to other studies described in section 2.2, this study investigated three different components, and also included the transportation and material exchange needed for remanufacturing. The results highlight several implications for the broader transition towards a circular economy. Remanufacturing can contribute to increased material reuse and extended product lifetimes by preserving a large share of the original components. However, the study shows that circularity does not automatically guarantee low environmental impact. Even though remanufacturing avoids production of entirely new components, considerable environmental impacts can still be generated from transportation and material replacement.

The result also indicate that when evaluating the environmental benefits of remanufactured components to newly manufactured ones, it is important to have a system perspective and consider the entire life cycle, including material exchange and all transportation related to the remanufacturing, rather than only focusing on the remanufacturing processes themselves.

The results also indicate that the environmental impacts of remanufacturing depend on how the systems are operated and organized logistically, as well as on which component that is being remanufactured.

7.8. Suggestions for Future Research

Several opportunities for future research were identified during this study. Future studies could compare the environmental impacts of remanufactured components with equivalent newly manufactured components to evaluate the overall environmental benefits of remanufacturing. Such comparisons could provide a better understanding of the conditions under which remanufacturing provides the greatest environmental advantages, and whether there are circumstances in which it is not environmentally beneficial.

Future work could also investigate further why the specific subcomponents are being replaced, both the mandatory replacements and the conditional ones. This could help identify opportunities to reduce the need for Material Exchange through improved component design, maintenance strategies, or remanufacturing methods.

Further research related to transportation and logistics could also be valuable. More advanced and dynamic logistics modelling could improve understanding of how transportation routes, load factors, transportation modes, and regional remanufacturing structures influence the environmental performance of remanufacturing systems. Future studies could also investigate more decentralized or regional remanufacturing systems and compare them with centralized remanufacturing structures.

It would also be valuable to assess the environmental impacts of remanufacturing for a larger variety of components to gain a broader understanding of different remanufacturing process steps and process alternatives. This could help identify opportunities to replace certain remanufacturing steps with less environmentally intensive alternatives and thereby reduce the impacts associated with the Remanufacturing Processes themselves.

Future studies could also include additional environmental impact categories and perform broader sensitivity analyses beyond Climate Change impacts. This may be especially relevant for future transportation systems, electrification, and impacts related to Material Exchange.

Finally, combining environmental assessments with economic and social analyses could provide additional insights into the sustainability of remanufacturing of components.

8. Conclusion

The purpose of this thesis was to map circular process steps and component flows in the remanufacturing and refurbishment of the heavy-duty truck components DPF, engine and electric vehicle battery. Additionally, it aimed to assess the environmental impacts associated with remanufacturing of DPF and engine through an LCA. The study also aimed to identify environmental hotspots and evaluate how assumptions related to transportation modelling influence the climate impact results.

The first research question: *What are the process steps and component flows within the remanufacturing and refurbishment of the DPF, engine and electric vehicle battery?*, is answered by the semi-quantitative MFA. It showed that the studied components differ in terms of process complexity, material exchange, and remanufacturing and refurbishment strategy. The DPF remanufacturing involved relatively few process steps, mainly related to cleaning and testing, while the engine remanufacturing was considerably more complex and included many subcomponents, process steps, machining activities, and material exchanges. The battery refurbishment involved fewer process steps, but because an electrical component is handled, the refurbishment process instead showed complexity related to safety and cleanliness requirements.

The second research question: *What are the environmental impacts associated with the remanufacturing and refurbishment of the DPF and the engine?*, is answered in section 6.3.2.1. Total Environmental Impact - DPF and 6.4.2.1. Total Environmental Impact - Engine. The results show that the environmental impacts differed considerably between the two components. For the DPF, transportation dominated most impact categories because there is no material exchange and limited impacts from the remanufacturing processes themselves. In contrast, for engine remanufacturing, new replacement materials represented the largest contributor in all impact categories.

The third research question was: *What are the hotspots in the circular processes of the two environmentally assessed components, and how do specific process steps compare in terms of their environmental contribution?* It was concluded that transportation is commonly one of

the main drivers of environmental impact for both the DPF and the engine. However, it is much more pronounced for the DPF, accounting for 65% of the Climate Change impact. Meanwhile, transport for the engine in the category Climate Change accounts for 30% and the Material Exchange for 60%. For the Remanufacturing Processes, the cleaning processes contributed most for the DPF, while the testing of the engine had the largest impact for that component.

The last research question: *How sensitive are the Climate Change impact results to assumptions regarding transportation modelling?*, was answered with a sensitivity analysis. The Climate Change impact results were strongly affected by transportation modelling assumptions. Increased load factors reduced Climate Change impacts for transportation for both components. The electric truck scenarios also showed large reduction potential for Climate Change impacts, although these results involved several modelling simplifications and uncertainties.

Overall, the results show that remanufacturing and refurbishment of components can look very different depending on the component characteristics. The environmental impact associated with remanufacturing depends on the type of component that is being remanufactured and the complexity of the remanufacturing process. The environmental impact is sensitive to transportation, and if material exchange is included, this can have a substantial effect. Therefore, it is important to include all these aspects when evaluating the environmental benefit of remanufacturing of components.

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Appendix A: Inventory Results - DPF

Table A1 below shows the LCI result for the transportation associated with remanufacturing of the DPF.

Type of transport	Transport mode	Amount [tonne*km]	Dataset
Transport of the core	Truck		market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 Cutoff, U - RER
	Ship		market for transport, freight, sea, container ship, heavy fuel oil transport, freight, sea, container ship, heavy fuel oil Cutoff, U - GLO
Transport to recycling	Truck		market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 Cutoff, U - RER

Table A2 below shows the Remanufacturing Processes for the remanufacturing process group Cleaning and Protecting Surfaces together with selected datasets.

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Cleaning 1		Confidential				
	Output	Waste: soot and ash		kg	Assumed together with	market for hazardous waste, for incineration

					Volvo Group employee	hazardous waste, for incineration Cutoff, U - RER without CH
Oven	Input	Electricity		kWh	Rating plate. Assumed utilization factor 0.5.	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR
Cleaning 2		Confidential				
	Output	Waste: soot and ash		kg	Assumed together with Volvo Group employee	market for hazardous waste, for incineration hazardous waste, for incineration Cutoff, U - RER without CH
Brushing	Input	Electricity		kWh	Measured data from year 2025	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR
		Confidential				
Spraying anti corrosion spray	Input	Anti-corrosion spray – inputs confidential		kg	Assumptions from internal documentation	Confidential
	Input	Electricity		kWh	Measured data from year 2025	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR

Table A3 below shows the Remanufacturing Processes for the remanufacturing process group Testing, together with selected datasets.

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Initial testing		Confidential				
Testing cleaning performance 1		Confidential				
Special testing	Input	Electricity		kWh	Rating plate. Assumed utilization factor 0.5.	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR
		Confidential				
Testing cleaning performance 2		Confidential				
Functional testing and engraving		Confidential				

Table A4 below shows the Remanufacturing Processes for the remanufacturing process group Other, together with input and output.

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Internal transportation - crane	Input	Electricity		kWh	Rating plate	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR
Dust collector	Input	Electricity		kWh	Measured data from year 2025	market for electricity, medium voltage electricity, medium voltage Cutoff, U - FR
Waste management, inert	Output	Waste: part of scrapped DPFs		kg	Volvo Group Employee	market for inert waste, for final disposal inert waste, for final disposal Cutoff, U - RoW

Appendix B: Inventory Results – Engine

Table B1 below shows the inventory data for the Material Exchange in material groups for the engine, together with the datasets used.

Material	Weight share of total mass [%]	Dataset	Dataset for Manufacturing process

Steel	60	market for steel, low-alloyed steel, low-alloyed Cutoff, U - GLO	market for metal working, average for steel product manufacturing metal working, average for steel product manufacturing Cutoff, U - GLO
Cast iron	20	market for cast iron cast iron Cutoff, U - GLO	-
Aluminium	10	market for aluminium, cast alloy aluminium, cast alloy Cutoff, U - GLO	market for metal working, average for aluminium product manufacturing metal working, average for aluminium product manufacturing Cutoff, U - GLO
Plastic	5	market for polypropylene, granulate polypropylene, granulate Cutoff, U - RER	market for injection moulding injection moulding Cutoff, U - GLO
Copper	2	market for copper, cathode copper, cathode Cutoff, U - GLO	market for wire drawing, copper wire drawing, copper Cutoff, U - GLO
Elastomers	<1	market for tube insulation, elastomere tube insulation, elastomere Cutoff, U - GLO	-
Ceramic	<1	market for ceramic tile ceramic tile Cutoff, U - GLO	-
Electronics	<1	market for electronics, for control units electronics, for control units Cutoff, U - GLO	-

Table B2 below shows the inventory data for the transportation connected to the remanufacturing of the engine, together with the dataset used.

Type of transport	Transport mode	LCI result [tonne*km]	Dataset
Transport of the added subcomponents	Truck		market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 Cutoff, U - RER
	Ship		market for transport, freight, sea, container ship, heavy fuel oil transport, freight, sea, container ship, heavy fuel oil Cutoff, U - GLO
Transportation of the core	Truck		market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 Cutoff, U - RER
	Ship		market for transport, freight, sea, container ship, heavy fuel oil transport, freight, sea, container ship, heavy fuel oil Cutoff, U - GLO
Transportation to recycling	Truck		market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 Cutoff, U - RER

Table B3 below shows the inventory data for the remanufacturing process group Internal transportation, together with selected datasets.

Specific process step	Input/ Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Internal Transportation	Input	Electricity		kWh	Volvo Group employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE

Crane	Input	Electricity		kWh	Volvo Group employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
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Table B4 below shows the Remanufacturing Processes for the remanufacturing process group Testing.

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Testing Crankshaft	Input	Electricity		kWh	Estimated by Volvo Group employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
		Confidential				
Crack detection testing Cylinder head	Input	Electricity		kWh	Estimated by Volvo Group employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
		Confidential				
Testing full engine	Input	Diesel production and combustion			Estimated by Volvo Group employee	market for diesel, burned in agricultural machinery diesel, burned in agricultural

						machinery Cutoff, U - GLO
Controlling and Inspection Crankshaft	Input	Electricity		kWh	Estimated by Volvo Group Employee and operators	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
		Compressed air		m3	Estimated by Volvo Group Employee and operators	market for compressed air, 700 kPa gauge compressed air, 700 kPa gauge Cutoff, U - RER
Testing EGR cooler		Confidential				
Drying EGR cooler		Electricity		kWh	Estimated by Volvo Group Employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE

Table B5 below shows the Remanufacturing Processes for the remanufacturing process group Washing, together with selected datasets. The asterisks show that the inputs, outputs, references, and assumptions and modelling choices are the same for all washing machines

Specific process step	Input/ Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Pre cleaning, full engine	Input	Electricity *		kWh	** Internal documentation and rating plates. Utilization	*** market for electricity, medium voltage electricity,

					factor 0.56 based on measurements.	medium voltage Cutoff, U - SE
	Input	Water *		kg	** Internal documentation and rating plates	*** market for tap water tap water Cutoff, U - RER without CH
	Input	Detergent *		kg	** Internal documentation and rating plates	*** market for cleaning consumables, without water, in 13.6% solution state cleaning consumables, without water, in 13.6% solution state Cutoff, U - GLO
	Output	Wastewater *		L	** Internal documentation and rating plates	*** market for wastewater, average wastewater, average Cutoff, U - RER without CH
Final washing, Cylinder block and Cylinder head		*			**	***
Middle washing, Cylinder block and cylinder head		*			**	***
Alka jet washing		*			**	***
FR washing		*			**	***

Tunnel washing		*			**	***
Tunnel washer blowdrying		*			**	***
Parts washing		*			**	***
EGR washing		*			**	***

Table B6 below shows the Remanufacturing Processes for the remanufacturing process group Machining and special repair, together with selected datasets.

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Controlling and inspecting, full engine	Input	Electricity		kWh	Estimated by operators	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
	Input	Compressed air		m3	Estimated by operators	market for compressed air, 700 kPa gauge compressed air, 700 kPa gauge Cutoff, U - RER
	Input	Oil		kg	Estimated by operators	market for lubricating oil

						lubricating oil Cutoff, U - RER
	Output	Waste		kg	Estimated by operators	market for hazardous waste, for incineration hazardous waste, for incineration Cutoff, U - RER without CH
Machining, cylinder head and cylinder block	Input	Electricity		kWh	Volvo Group Employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
	Input	Grease		kg	Estimated by operators	market for lubricating oil lubricating oil Cutoff, U - RER
	Input	Water		kg	Estimated by operators	market for tap water tap water Cutoff, U - RER without CH
	Output	Wastewater		L	Estimated by operators	market for wastewater, average wastewater, average Cutoff, U - RER without CH
Machining, cylinder head and	Input	Electricity		kWh	Volvo Group Employee	market for electricity, medium voltage

cylinder block						electricity, medium voltage Cutoff, U - SE
Controlling and inspecting Cylinder head		Confidential				
Polishing camshaft	Input	Electricity		kWh	Assumed and checked with Volvo Group employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
Machining cylinder head		Confidential				
Machining connecting rod		Confidential				
Machining crankshaft		Confidential				
Average machining	Input	Electricity			Estimated and checked with Volvo Group Employee	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
Special repair		Confidential				

Table B7 below shows the Remanufacturing Processes for the remanufacturing process group Blasting and burning, together with selected datasets.

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Blasting	Input	Blasting media		kg	Based on yearly consumption	Type of blasting media is confidential
	Input	Electricity		kWh	Estimated based on rating plate	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
	Input	Compressed air		m ³	Technical specification of machine	market for compressed air, 700 kPa gauge compressed air, 700 kPa gauge Cutoff, U - RER
	Output	Waste: part of blasting media that goes to landfill		kg	From renovator site	Dataset representing landfill of blasting media
Oven	Input	RME		kg	Based on yearly consumption	esterification of rape oil fatty acid methyl ester Cutoff, U - RER without CH
	Input	Electricity		kWh	Technical specification of machine	market for electricity, medium voltage electricity,

						medium voltage Cutoff, U - SE
	Output	Carbon dioxide		kg	Estimated based on emissions when burning diesel	Flow: Carbon dioxide, from soil or biomass stock
	Output	Carbon monoxide		kg	Estimated based on emissions when burning diesel	Flow: Carbon monoxide, from soil or biomass stock
	Output	Nitrogen oxides		kg	Estimated based on emissions when burning diesel	Flow: Nitrogen oxides
	Output	Particulate Matter		kg	Estimated based on emissions when burning diesel	Flow: Particulate Matter, < 2.5 um

Table B8 below shows the Remanufacturing Processes for the remanufacturing process group Assembly and disassembly, together with selected datasets.

Specific process step	Input /Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Disassembly, full engine	Input	Electricity		kg	Estimated by Volvo Group Employee and operators	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
	Input	Compressed air		kg	Estimated by Volvo Group Employee and operators	market for compressed air, 700 kPa gauge compressed air, 700 kPa gauge Cutoff, U - RER

Assembly, full engine	Input	Electricity		kWh	Estimated by Volvo Group Employee and operators	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
	Input	Compressed air		m3	Estimated by Volvo Group Employee and operators	market for compressed air, 700 kPa gauge compressed air, 700 kPa gauge Cutoff, U - RER
	Input	Oil		kg	Estimated by operator	market for lubricating oil lubricating oil Cutoff, U - RER
	Input	Denatured alcohol		kg	Estimated by operator	market for ethanol, without water, in 99.7% solution state, from fermentation ethanol, without water, in 99.7% solution state, from fermentation Cutoff, U - GLO
	Input	Silicone		kg	Estimated by operator	market for silicone product silicone product Cutoff, U - RER
	Output	Alcohol emission to air		kg	Estimated by operator	NMVOC, non-methane volatile organic compounds
Cylinder head disassembly	Input	Electricity		kg	Estimated by operator	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
	Input	Compressed air		kWh	Estimated by operator	market for compressed air, 700 kPa gauge compressed air, 700 kPa gauge Cutoff, U - RER

Cylinder block disassembly	Input	Electricity		kg	Measurement and rating plates from similar machine	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
Valve seat removal, cylinder head	Input	Electricity		kg	Measurement and rating plates from machine	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
Disassembly, connecting rod	Input	Electricity		kWh	Estimated from rating plates	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE

Table B9 below shows the Remanufacturing Processes for the remanufacturing process group Other, together with selected datasets.

Specific process step	Input/Output	Specific input/output	Amount	Unit	Reference and assumption	Dataset
Painting	Input	Paint		kg	Based on yearly consumption	market for alkyd paint, white, without solvent, in 60% solution state alkyd paint, white, without solvent, in 60% solution state Cutoff, U - RER
	Input	Electricity		kg	Estimated	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE
	Input	Plastic film		kg	Estimated	market for polyethylene, low density, granulate polyethylene, low density, granulate Cutoff, U - RER

	Input	Tape		kg	Estimated	market for sulfite pulp, bleached sulfite pulp, bleached Cutoff, U - GLO
	Output	Waste: plastic film and tape		kg	Based on amount of input	market for hazardous waste, for incineration hazardous waste, for incineration Cutoff, U - RER without CH
Extra materials/auxiliary	Input	Denatured alcohol		kg	Estimated and checked with operator	market for ethanol, without water, in 99.7% solution state, from fermentation ethanol, without water, in 99.7% solution state, from fermentation Cutoff, U - GLO
	Input	Absorbents for cleaning		kg	Estimated and checked with operator	market for sulfite pulp, bleached sulfite pulp, bleached Cutoff, U - GLO
	Output	Waste: absorbents		kg	Estimated and checked with operator	market for hazardous waste, for incineration hazardous waste, for incineration Cutoff, U - RER without CH
	Output	Alcohol emission to air		kg	Estimated and checked with operator	NMVOC, non-methane volatile organic compounds

Appendix C: Environmental Impact Results – Engine

Figure C1 below shows the environmental impact results for the engine in the remanufacturing process group Washing.

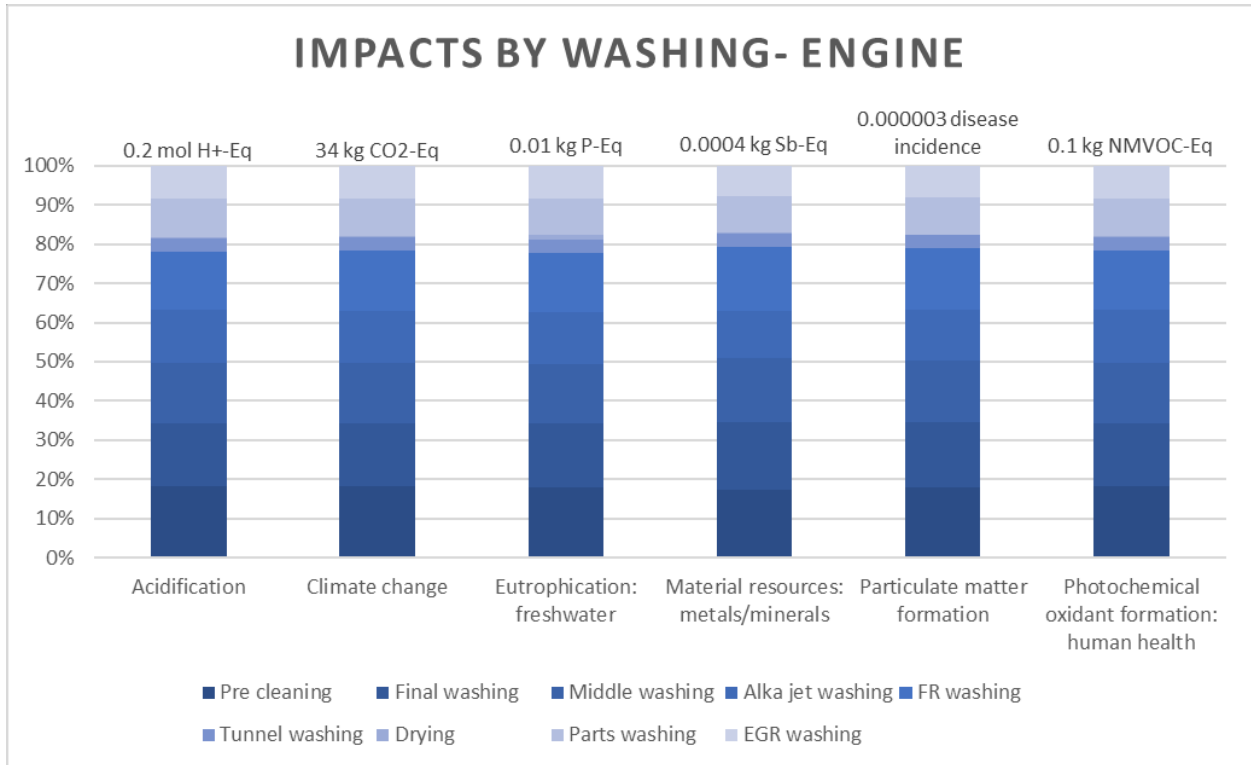


Figure C2 below shows the impacts by transport split into the different types of transport, together with the total environmental impact for the engine.

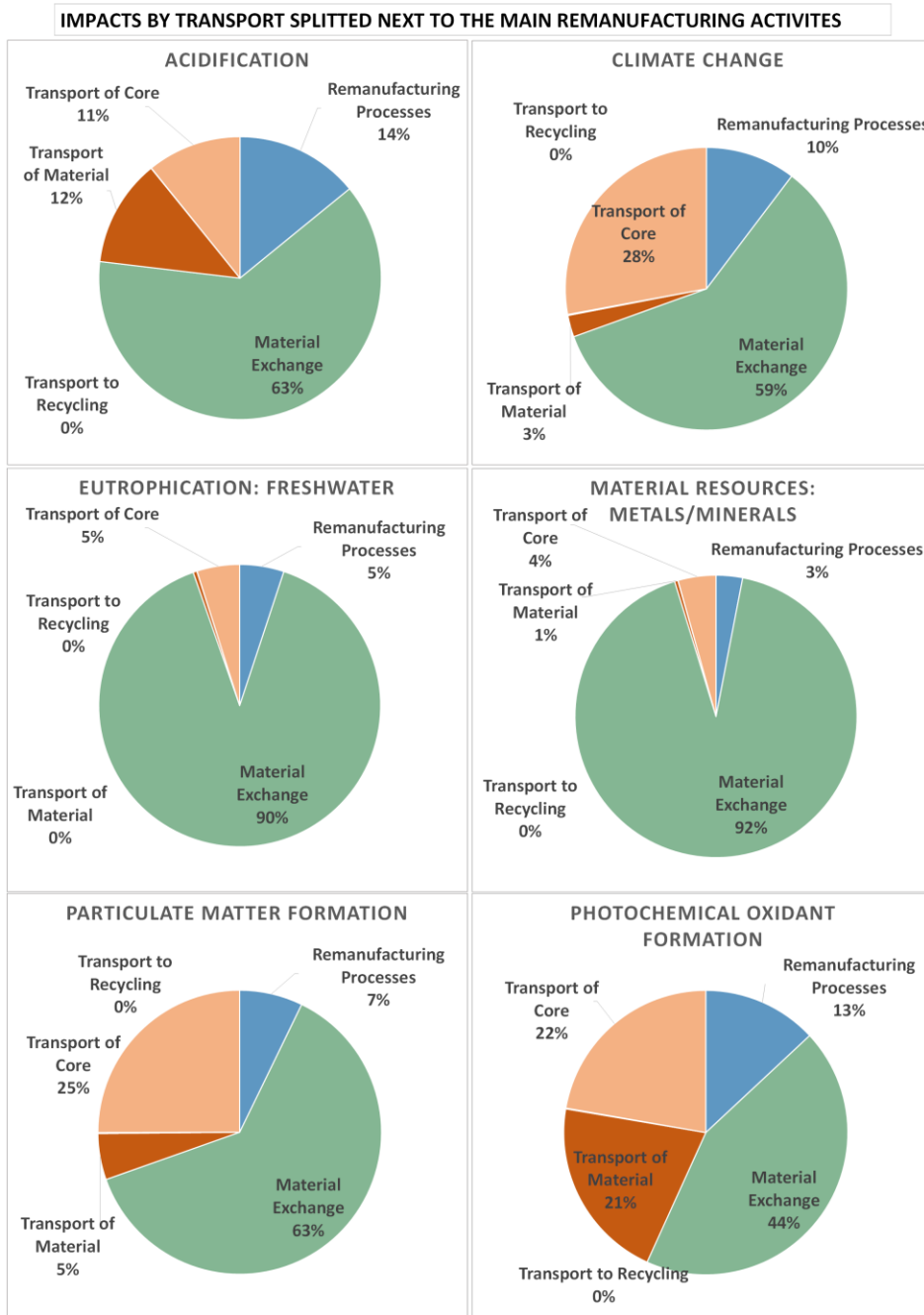
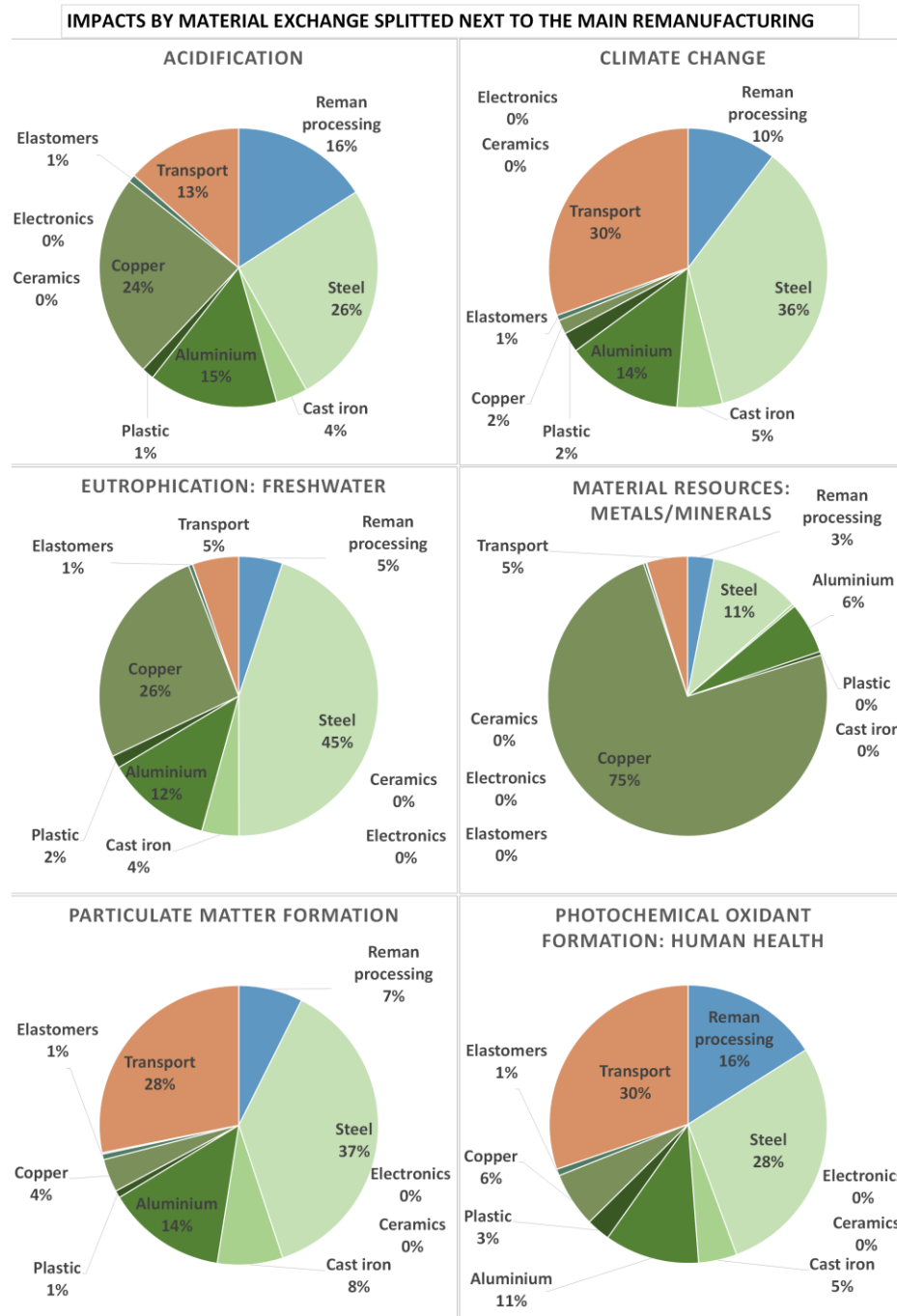


Figure C3 below shows the impacts for Material Exchange for all materials, together with the total environmental impact of the engine.



Appendix D: AI Use Declaration

AI tools, specifically ChatGPT and Gemini, have been used as supportive tools for writing this thesis. It has been used for language assistance, including grammar correction, sentence refinement, and improving the clarity and readability of specific sentences. AI was also used to provide guidance on formatting figures in Excel and inspiration regarding the report layout and overall structure.

The AI tools were not used to generate original scientific content, interpret results, develop arguments, or draw conclusions. The authors take full responsibility for the content presented in this thesis. AI was only used as a supportive writing and productivity tool.

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