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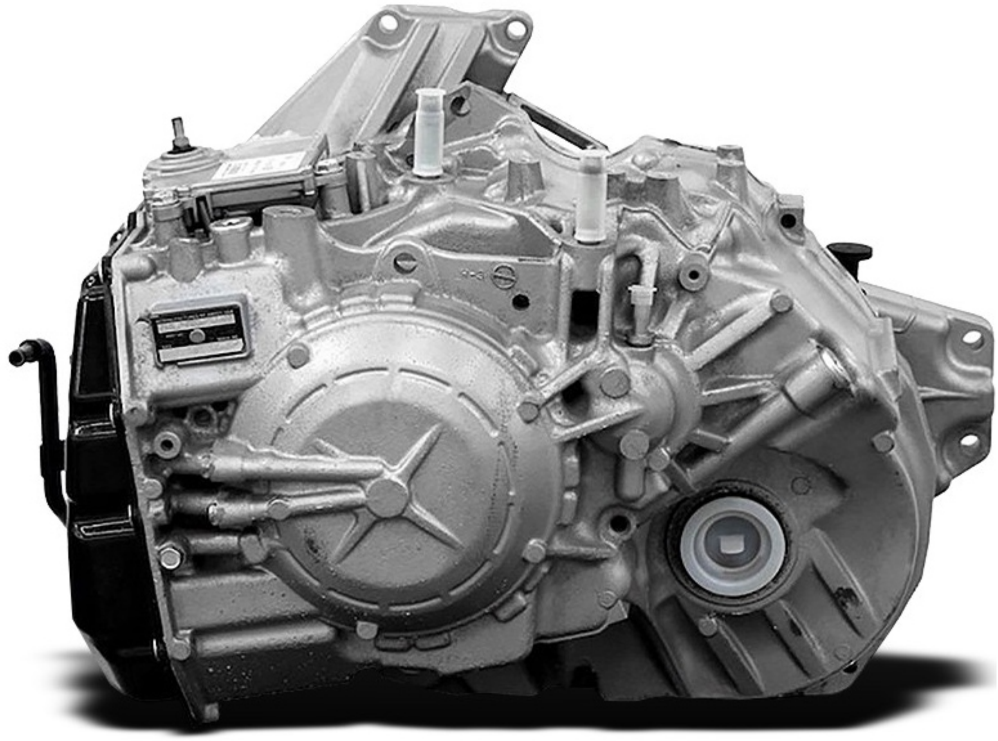

Remanufacturing in Circular Economy: A Gearbox Example

A Comparative Life Cycle and Cost Assessment

Master's thesis in Sustainable Energy Systems

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Cover: An image of an AWF 21 6-speed automatic transmission [1].

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Abstract

To have the lowest impact on the environment, it is important to shift from the linear economy characterized by take-make-use-dispose to the circular economy focusing on re-make and re-use. This is the case when it comes to a wide range of spare parts at Volvo Cars. The primary purpose when the remanufacturing program started was because of the shortage of raw materials during the Second World War. To be able to judge the environmental consequence of such a program, a Life Cycle Assessment was performed on both a newly manufactured and a remanufactured gearbox. The assessment also included a Life Cycle Cost Analysis to evaluate the economic benefits of using the remanufacturing program.

The study included the life cycle of around 30 components in a gearbox, constituting of the largest share by weight of the gearbox. The modeling was done using OpenLCA, a software which performs the environmental impact calculations for different materials.

The results showed that the remanufacturing of the gearbox reduced the global warming potential (CO_2-eq) by 36% compared to a newly manufactured one. The major contributing phase to the emissions is the extraction of steel and aluminum, which justifies the result (since a remanufactured one requires less extraction).

Looking at each life cycle phase separately, the use phase was by far the largest contributor in terms of environmental impact. This shows that the biggest potential in environmental saving would be by implementing more efficient gearboxes with less losses.

The conclusion of the study is that it is better to use remanufactured gearboxes as a spare part as it is not only more environmental friendly, but also more cost efficient.

Keywords: Circular economy, Remanufacturing, Life Cycle Assessment (LCA), Life Cycle Cost (LCC), Gearbox.

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Pranav Gabhane and Mohamad Kaddoura, Gothenburg, June 2017

Acronyms

CLSC: Closed-Loop Supply Chain
EMAF: Ellen MacArthur Foundation
EOL: End Of Life
IMDS: International Material Data System
ISO: International Organization for Standardization
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
IPCC: United Nation Intergovernmental Panel on Climate Change
REES: Resource Efficient and Effective Solutions
STS: Scandanavian Transmission Service AB
VCC: Volvo Car Corporation
VDA: The German Association of the Automotive Industry

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1
Introduction

The United Nation's 21st Conference of Parties (COP21), held in Paris in 2015, aimed at limiting global warming to 2 degrees Celsius [2]. With decreasing natural resources and increasing environmental crisis, achieving this target has become the need of the hour.

The automotive industry depends on various raw materials and scarce metals in the manufacturing phase, which puts a limit on the future development of this sector. The World Steel Association estimates, that the automotive sector is responsible for 12 percent of the overall global steel consumption [3]. It is also responsible for 60 percent of the global lead consumption according to US Geological Survey, the reserves of which are thought to run out by 2030 [4]. Aluminum, another important metal in car production, is responsible for around 1.1% of the global Greenhouse Gas emissions during it production [5]. This pressure on metals and emissions resulting from their production has resulted in increased prices and difficulties in securing the supply chain for the process. In order to prevent this and achieve the 2 degree target, recycling and reuse at the End of Life (EOL) of vehicles has received a major attention. It was found that the largest reduction potential in energy use and Greenhouse Gas emissions is through recycling of scrap, that is mainly found in end-of-life vehicles [6].

Even if the world will not run out of these metals in the near future, the supply could be affected by other factors like geopolitics and trade agreements. This leads manufacturers to rethink the way they work, and strive to shift from linear economy to circular economy. This shift would not only solve the problem of scarcity of metals, but might also reduce the environmental and economic impacts of manufacturing. Since the total number of end-of-life vehicles in EU in 2014 was around 6 million cars [7], it is more efficient to use this above ground urban mine rather than geological mines. The utilization of these resources could be through reusing, remanufacturing, or recycling.

In Europe, regulations have been strict according to the utilization of end-of-life vehicles. According to Directive 2000/53/EC on end-of-life vehicles, countries should reach at least 80% of reuse and recycling and 85% of reuse and recovery of end-of-life vehicles by 2006. [8]. All intended countries were able to reach these levels (except for Malta), where Sweden for example achieved 84% of reuse and recycling and 91% of reuse and recovery in 2014 [7]. The directive also set a stricter target of at least 85% of reuse and recycling and 95% of reuse and recovery of end-of-life vehicles by

2015, which were hard to be reached by most countries.

Volvo cars, being the largest automotive manufacturer in Sweden, has started the remanufacturing journey for a long time. In 2015, around 15% of the spare parts sold came from remanufactured parts [9]. The following study assesses the environmental and economic impacts of remanufacturing of automatic gearbox, which might influence Volvo's strategy in the future, by designing remanufacture-friendly vehicles. A previous study done by Volkswagen on manual gearboxes concluded that energy use is reduced 33% when going to remanufacturing [10]. The previous study had not taken into account the use and end-of-life phase, and used a generic 50% injection rate for all the sub-component.

2
Background

2.1 Volvo Cars and STS

Volvo Cars
Volvo Cars is a Swedish luxury vehicle manufacturer established in 1927 as a subsidiary of SKF. Its headquarters are located on the Hisingen island of Gothenburg, Sweden. In 2010, it was acquired by a Chinese automotive giant, Geely. It manufactures and markets sports utility vehicle, sedan, coupes among other types of vehicles.

Due to World War II, there was a sudden loss of metals and materials required for many manufacturing processes. Thus, to overcome the shortage of raw materials, Volvo Cars began remanufacturing its old car components to meet its needs. IN 1945, an exchange system was established to remanufacture replaced parts to their original specifications, realising both environmental and financial savings. Around 780 tonnes of steel and 300 tonnes of aluminium were saved by Volvo Cars in 2015 using only remanufacturing. Under this system, it is obligatory that the participating dealers return the replaced components and Volvo Cars' external suppliers remanufacture the qualifying components to their original specifications. Thus the system helps in remanufacturing everything from gearboxes to injectors and electronic components, and these components have the same quality as regular spare parts [11].

STS AB
Scandinavian Transmission Service AB is one of the leading industrial transmission remanufacturers in the European market. They are located in Stenungsund, in western Sweden. Their main customers are the major vehicle spare part manufacturers and thus cater to most European car brands with remanufactured spare parts. Being a specialist in transmission, they also extend their services to the various car manufacturers with Original Equipment Manufacturer's (OEM) support [12].

2.2 IMDS and VDA Classification

The International Material Data System or the IMDS as it is most commonly known, is a global standard or a directory which is used by most automotive industries. All the information regarding the various substances or materials used in the manufacturing of any automobile is collected, maintained, analysed and archived. Due to the implementation of the End-of-Life Vehicle Directive in June 2013, all the suppliers to the automotive industry must declare the composition of the various materials used in the manufacturing of the vehicle parts [13].

VDA classification:
VDA classification is a German quality management standard for material classification published by the German Association of Automotive Industry or VDA. All the automotive companies must stick to the classification given by VDA regarding material components and specifications, especially when reporting to IMDS. This is done to ensure a standard quality for all the materials used in manufacturing any automobile [14].

2.3 Circular Economy and Remanufacturing

Throughout the end of the 18th century, industrial revolution started, moving the industry to a new manufacturing process. This industry was based on a linear model characterized by 'take-make-use-dispose'. Suppliers extract materials from biosphere, companies manufacture and sell products to consumers, and the product ends up as waste at their end of its life. With some materials and metals starting to become scarcer, and due to geopolitical conflicts, the prices of these materials are increasing, and the availability of them for manufacturers is being threatened. This has lead manufacturers to try and close the loop by adopting a new model- circular economy.

Circular Economy is a vision for a new type of industrial economy that focuses on resource optimization by reducing the waste and avoiding pollution either by design or intention. According to Ellen MacArthur Foundation (EMAF), it is based on few principles. It should be targeted to 'design out' waste, differentiate between 'consumable and durable components' of the product, and energy used during its life cycle should be renewable [15]. Furthermore, to better understand how circular economy could be applied to the system, EMAF provides the butterfly diagram (Figure 2.1) as a guideline with basic circular economy processes. According to the nature of the product (containing technical or biological materials), different processes could be applied. Besides, it is usually more efficient (less energy intensive) to start by closing the inner loops before focusing on the outer loops. In some cases, mainly when the product is not designed for circular economy, it is not possible to work on the inner loops. In extreme cases, neither loops could be triggered, and a leakage will occur in the system (energy recovery and/or landfill).

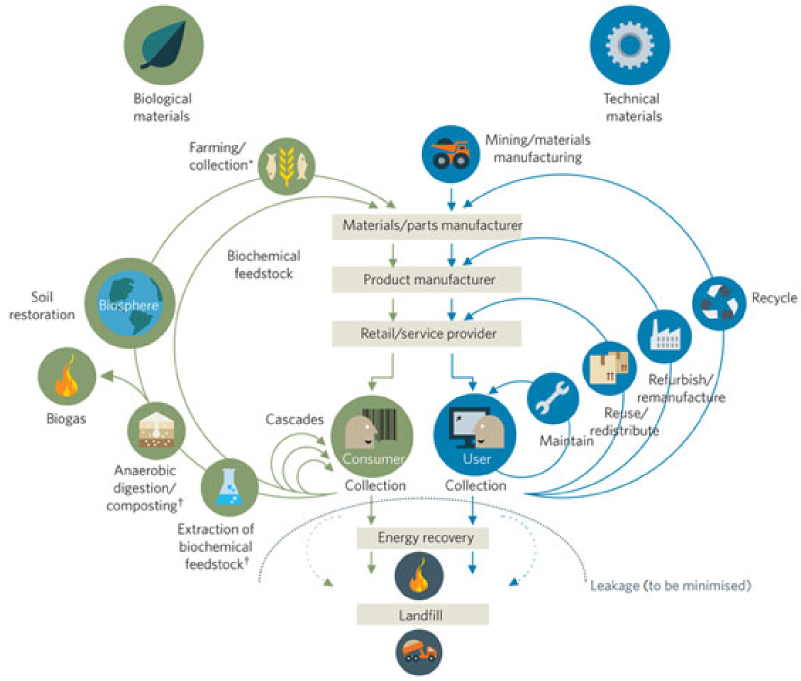

Figure 2.1: The circular economy- an industrial system that is restorative by design [15].

Component Remanufacturing

One of the inner circles in the butterfly diagram is remanufacturing. This process includes dis-assembly of a product to its sub-components, then performing remanufacturing on those components before assembly again. Functioning parts which are not worn away and could be used again will be used in new products. This process includes quality assurance and potential enhancements or changes to the components [15].

Remanufacturing has great advantages both economically and environmentally. It helps reducing the burden on customers because these products are usually less expensive, and cost approximately 60-80% of the cost of a new one.They are cost efficient because there is no need to obtain new raw materials and as the product is already manufactured, it only needs to be restored to its original (or better) quality. Sometimes when the demand for a certain product is very high, a remanufactured product is available with a shorter lead time [16].

Moreover, less energy is used to remanufacture certain products as compared to manufacturing them from scratch. It thus reduces CO_2 emissions and also limits the amount of waste ending up in the landfill [16]. A study found that remanufacturing mobile phones is more environmental and economical than manufacturing new ones [17].

Finally, it helps the local remanufacturing industry and public because it generates employment opportunities. In Sweden for example, circular economy (where remanufacturing is included) could create 100,000 jobs [18].

Circular economy in general, and remanufacturing in specific, still faces a lot of burdens to become widely used. Most of the products are not designed for circular economy, and it is hard for the industry to change the way they do their work, and easier for it to stick with business-as-usual [19]. Besides, being cheaper is not always an incentive for customers, because of the belief that remanufactured products are of a lower quality. Hazen et. al found that shaping the customers' attitude towards remanufactured products is the most important factor in shifting towards remanufactured products [20].

3

Technical Overview

3.1 Raw material and Manufacturing Process

The following section discusses how the essential raw materials required for the manufacturing of various components in the gearbox are produced. A description of the various processes that the components undergo has also been mentioned.

Steel Production:
Iron making and steel making have existed for many years. The two terms are different from each other in the sense that, iron making precedes steel making. The extracted iron ore usually contains a lot of impurities and hence undergoes many processes to form purified iron [21].

The steel making process initiates with the processing of the iron ore. The iron ore rock is ground and with the help of magnetic rollers, the ore is extracted. In order to make steel, facilities use a mixture of iron ore and coke and heat it in a blast furnace to produce pig iron. Coking coal is converted to coke by removal of impurities at high temperatures (1000-1100°C) under the absence of oxygen [22].

There are two main furnaces used to produce steel, namely, Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF). The molten liquid , also called hot metal, along with steel scrap are the main materials used in BOF process. First, the hot metal is poured into a ladle. After that, the furnace is filled with ingredients, a process known as charging, and then subjected to streams of high velocity oxygen. It oxidizes the carbon and silicon present in the hot metal thus increasing the temperature well enough to melt the scrap. In an EAF, on the other hand, recycled steel scrap is melted, and the molten steel obtained is refined in a secondary refining process before being drawn out into slabs, blooms or billets [23].

Aluminum Production:
Despite being one of the most abundant element on the Earth, aluminum is not available in its metallic form but is present in its ore, bauxite. Bauxite mining involves extraction of the ore, crushing, and then transportation to the factories to obtain aluminum oxide, also known as alumina, using Bayer's process. This process involves digesting, clarification, precipitation and calcination. Once alumina is refined, it is sent to electrolytic smelters to extract aluminum from alumina. For every two tonnes of alumina, one tonne of aluminum is produced. Pure aluminum,

being very soft metal, is mixed with other metals to form an alloy [24].

Milling process:
Milling is a type of machining process in which metal is removed by a rotating, multi edge cutter and multi-axis movement of the workpiece. It is a type of cutting process wherein continuous cycles of feeding of the cutting tool removes the metal and generates chips. This process has a lot more machine types, tooling, and workpiece movement as compared to other machining processes. There are two main types of milling operations: up milling and down milling. As the name suggests, up milling basically means that the cutting tool removes the metal in the opposite direction of the feed. The metal removal process begins with the removal of thin metal and then slowly increase in thickness. This is also called as conventional milling.

Down milling, on the other hand, means that the material is cut along the direction of the cutting tool. The chip formed is thicker in the beginning and thins out in the end. This is also called climb milling. All milling machines from horizontal milling machines to CNCs use common operating parameters. The most important among them are cutting speed, feed rate, axial depth of cut, radial depth of cut [25].

Drilling Process:
Drilling is an economical way of removing metal to create precise holes or cavity on the work piece. The drilling operation is dependent on the cutting speed, size of the drill bit, metal removal rate and feed rate. There are many types of drilling processes such as upright drilling, bench drilling, radial drilling, and Computer Numerical Control (CNC) drilling. Commonly in the industries, CNC drilling is usually preferred as it is completely automated and precise holes can be made [26].

Casting Process:
Casting is the most widely used method to obtain aluminum products. Metal casting begins by pouring hot liquid metal into moulds or casts. Moulds are made from refractory materials such as sand or ceramic. They have the inverse shape of the material that is casted. The liquid metal is poured in the mould cavity and then allowed to cool down. Once the metal takes the shape of the cast and solidifies, the mould is broken and the solidified metal is separated. The biggest advantage that casting offers in manufacturing process is that it can produce complex shapes with internal cavities very easily. It is also economical as there is no wastage of the metal, since excess metal is remelted and reused again [27].

There are various types of casting processes. Some of them are sand casting, shell mould casting, ceramic mould casting, investment casting, vacuum casting, die casting, and centrifugal casting. Die casting is a type of permanent mould casting process. Surface finish and tolerance of die casting is so good that sometimes post production processing is not required, which is also why they are expensive and require more time to produce. There are two main types of die casting process: hot chamber process and cold chamber process. Hot chamber process is used to produce zinc alloys and magnesium cast products, whereas cold chamber process cast metals with high melting points such as aluminium and copper and its alloys [28].

3.2 Gearbox AWF-21AWD Architecture and Description

The AWF-21AWD is a 6-speed automatic transmission (gearbox) which is electronically controlled by a Transmission Control Module (TCM) or a computer. It is manufactured by Aisin Warner (AW) in Japan.

Figure 3.1 indicates where a gearbox is located in a car. The figure also indicates what other components are connected to the gearbox. Table 3.1 shows the names of the parts in the figure.

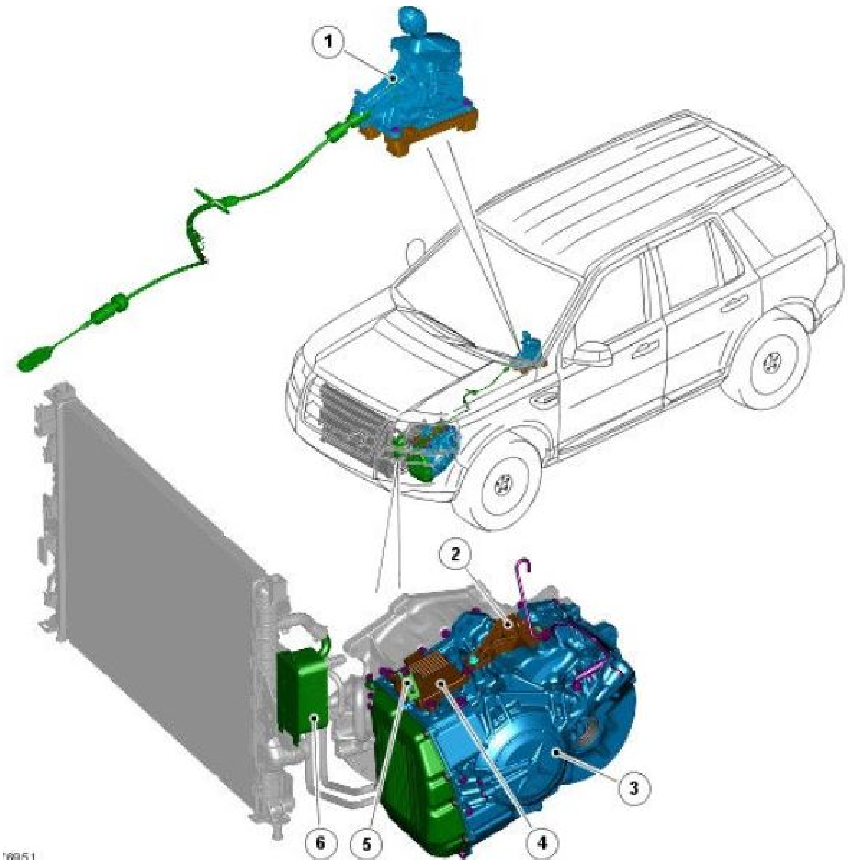

Figure 3.1: Location of the gearbox in a car [29].

Item	Description
1	Transmission selector lever assembly
2	Cable Bracket
3	Automatic Transmission
4	Transmission Control Module
5	Lever Arm
6	Transmission Fluid Controller

Table 3.1: Key map for the parts used in 3.1

The automatic transmission is controlled by the TCM which allows the transmission to be operated by selecting either of the P, R, N, D options on the selector lever. The other main components that are included in an automatic transmission are shown in Figure 3.2, and will be further illustrated.

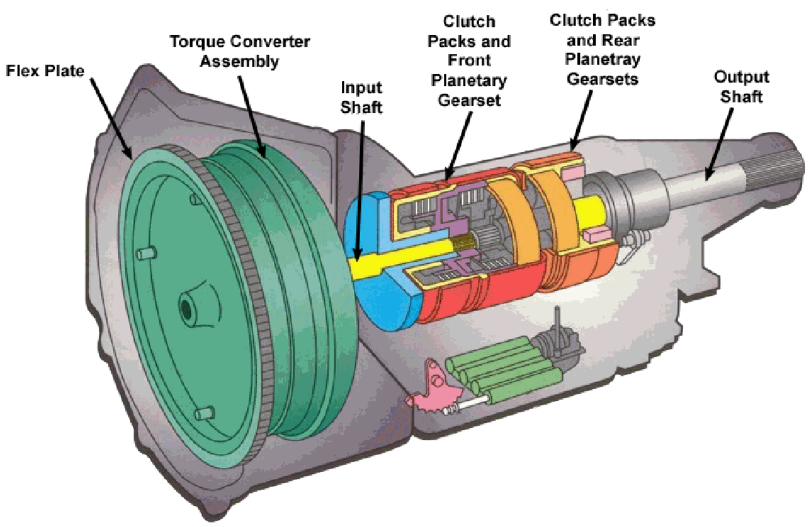

Figure 3.2: Various components in a gearbox [30].

Torque converter:
Theoretically, without a clutch the engine would stall when slowing down as the transmission load would push the engine to run below its minimum rev limit. But in an automatic transmission, the torque converter performs the same function as the clutch.

The output shaft from the engine is connected to the torque converter. A torque converter is a coupling device that transfers rotating power from an engine to an automatic transmission. A torque converter usually consists of 3 parts: pump driven by the engine, turbine driving the transmission, and stator to guide the direction of flow of fluid [31]. Figure 3.3 shows the inside components of a torque converter.

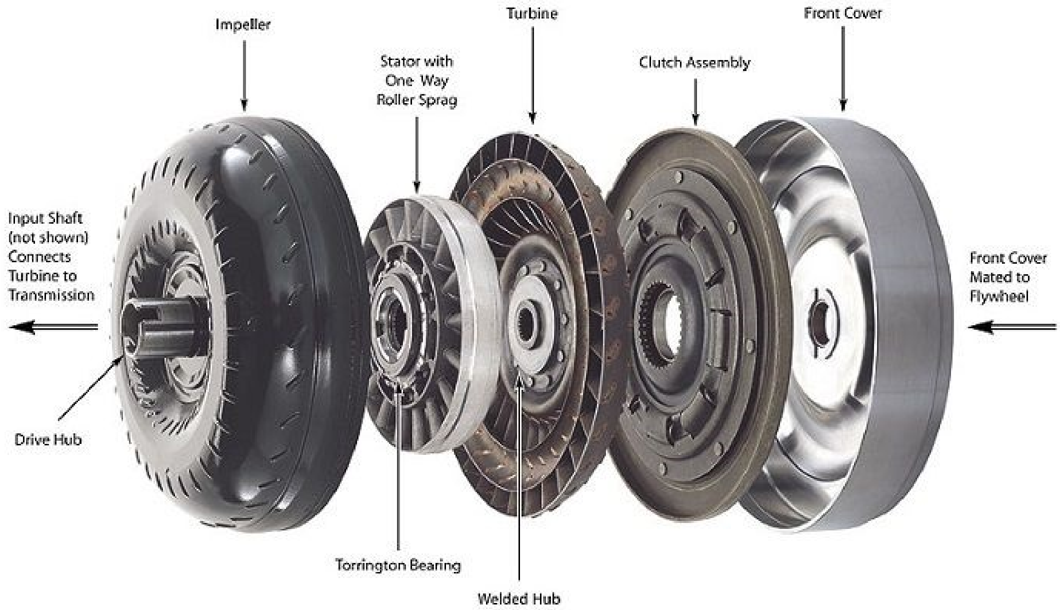

Figure 3.3: An exploded view of a torque converter [32].

The torque converter allows the engine to run even when the car is not moving. This is done by reducing the output torque to the transmission. The torque converter has an impeller which rotates when the fluid is pumped into it, thus helps in providing the required torque to the transmission shaft [33].

In a manual transmission, a clutch assembly helps in engaging and disengaging various gears for various speeds. Unlike manual transmission, the gears in an automatic transmission system are always engaged. So when the driver brakes, the gears get locked. The torque converter is responsible for activation of clutch and brakes by the use of the Automatic Transmission Fluid (ATF) through hydraulic pump. The fluid pressure is what activates the clutches and brakes. A hydraulic control unit sends signals and thus helps in changing the gears and locking torque converter.

Planetary gear set:
A system of various gear ratios that get engaged or disengaged as the vehicle accelerates or decelerates. Thus altering the speed of rotation of the output shaft depending on which planetary gear is engaged. Table 3.2 show the gear ratios for different speeds for the AWF-21 gearbox, that is used for the study. The maximum shift speeds for the gearbox are 7000 rpm (up to 350 Nm) and 6500 rpm (350 Nm to 400 Nm) [34].

1	2	3	4	5	6	R	Final Drive
4.148	2.370	1.556	1.155	0.859	0.686	3.394	3.20

Table 3.2: Gear Ratios for different speeds for AWF-21

Band brakes:
Any band which locks a spinning component to the case, such as a planetary gearset, is called a brake (B). The gearbox under study has two brakes: The B1 brake is a band which engages the rear planetary sun gear and is usually applied in the 2nd and 6th gear.

Clutches:
A clutch is one of the most important component in any automobile. It helps in the transmission of power from the driving part of the automobile, the engine, to the driven part, the wheels [35].

There 3 main types of clutches in this gearbox, they are:

- C1 clutch: When the vehicle is driven, the C1 clutch engages the front planetary carrier with the rear planetary sun gear. When the clutch is released clutch and ring gear rotate at different speeds.
- C2 clutch: The C2 clutch engages the turbine shaft to the rear planetary carrier. It engages the 4th and 6th driven gears.
- C3 clutch: The C3 clutch engages the front planetary carrier to the rear planetary sun gear thus engaging, the reverse, 3rd and 5th gear. [36]

Differential:
The wheels of any automobile that receive power from the engine are called the drive wheels. When the vehicle is about to take a turn, the wheels will receive equal power from the engine, which means that both the wheels will rotate at the same speed. In such a case, the vehicle will lose traction and slip. In order to prevent this, a differential is used. Figure 3.4 shows a cut open view of a differential and shows the various components present in it.

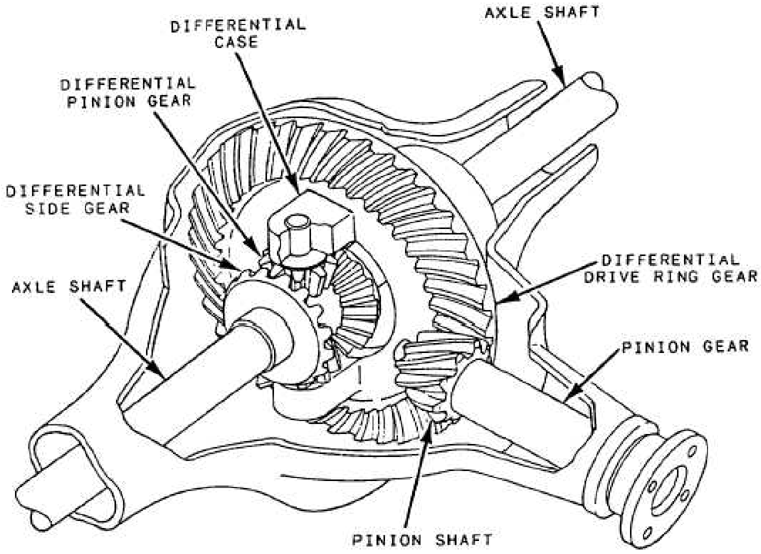

Figure 3.4: A cut open view of a differential [37].

A differential consists of pinion gear, ring gear, differential gears and axle shafts. When the vehicle is traveling in a straight line path, all the gears run at the same speed, however when the vehicle rounds a corner, the differential gears connected to the drive wheels run at different speeds. The inner wheel travels for a shorter distance and thus rotates at a slower speed as compared to the outer wheel which travels for a longer distance and rotates at a higher speed. A differential thus provides different rotational speeds to the drive wheels, because of which the vehicle does not slip from the road [38].

4
Methodology

The study is divided into two parts, Life Cycle Assessment (LCA) and Life Cycle Cost (LCC). Each part will be a comparative study between a newly manufactured gearbox and a remanufactured one. The framework for LCA and LCC will be explained in this chapter, together with the software used in the study.

4.1 LCA Framework

Life Cycle Assessment (LCA) is a technique used to understand and address the environmental impacts of any product in its entire life cycle. This includes raw material extraction, manufacturing, transportation, use, and end-of-life treatment. The LCA technique is used for various objectives. It could be used to identify opportunities of environmental improvement during the entire life cycle of a product. It could also help in decision making for different stakeholders, to know which products are environmental friendly and which are not. Besides, some times it is used for marketing purposes in companies to declare the environmental-friendliness of their product to the customers [39].

According to the ISO 14040:2006 standard, to conduct an LCA study, four phases should be included:

Goal and Scope Definition phase

In this phase, the product to be studied and the purpose of conducting the study is clearly defined. It should also include the audience to which the study would be intended to. The goal should be as specific as possible for the study to have a more focused aim.

This is followed by the specifications of the modelling, like choosing the functional unit, which serves as a quantitative term that describes the function of the product, and acts as a comparison basis. The choice of the system boundaries is also important, which includes natural, technical, and geographic boundaries. Extending or reducing the boundaries would have great effect on results. The time horizon for which the study would be valid is decided upon here, which will affect the choice of available technologies and standards to be used.

Allocating the emissions caused by processes with multiple outputs or damage due to open-loop recycling is a tricky part that has to be dealt with. A solution for the first problem could be allocation based on physical relationship. An example in this study would be estimating the fuel consumption caused by the gearbox when the aggregated emissions for the whole car are known. Knowing the science behind the function of the gearbox, and that losses occur due to friction and other forces, allocation to the gearbox could be done. Solving the open-loop recycling could also be done in various ways. An approximation with closed loop recycling is a possible solution. In the gearbox example, the recycled material is used in other industries, but since steel and aluminum does not loose too much quality after recycling, it could be assumed that it is used in the gearbox production, and the loop is closed. However, this was not used in this study. Another allocation method, which is the one used in this study, is the cut-off method. In this method, only emissions directly caused by product are assigned to it. Thus the remanufactured one does not carry the burden of extraction of raw material, and the recycling phase does not give credit to the raw material extraction in the case of a newly manufatured gearbox.

Another significant choice is that of the type of environmental impact to be considered. This choice affects the data collection later, knowing which information is needed and which is not. Common impact categories are global warming, acidification and eutrophication. For example, Global Warming category, which was used in this study, describes greenhouse gases in the atmosphere, which absorb infrared radiations and heat up the atmosphere. Each greenhouse has different capacity to absorb and is modelled accordingly. Besides, GHGs have different time spans in the atmosphere, so their efects change accordingly.

Inventory Analysis phase

This phase includes drawing the detailed flow chart of the system according to the decisions made in the goal and scope definition. It usually contains raw material production, manufacturing processes, use, transportation, and end-of-life. This will generate a mass and energy balance for the system, only including those relevant for environmental studies.

Data collection is the second step, where information regarding all inputs and outputs to the system are gathered. This includes raw materials, products, and emissions. In this study, most data was collected from the IMDS, and from interviews with people in Volvo Cars and STS. Besides, Ecoinvent database has been used for most of the upstream processes for raw material production and manufacturing processes, and some processes for use and end-of-life phase.

The final step is to calculate the aggregated input and output of the system in terms of resource use and pollutant emissions per functional unit. These results are displayd in a way that fulfil the purpose of the study.

Impact Assessment phase

Life Cycle Impact Assessment is used to aggregate resources or emissions having the same consequence together. This way, these emissions could be understood in an environmental way, and their effects could be easily communicated.

This starts with classification of inventory data (resources and emissions) according to their environmental impact. It is followed by characterization, or giving a relative contribution of each inventory parameter to the specific impact category. For example, all greenhouse gases contribute to global warming, but each gas has different effect according to different scientific research. Thus, each one has its own characterization factor based on that. A more aggregated result could be achieved by having more weighting systems, but the numbers may become of less relevance. For this study, only Global Warming Potential (GWP) was used as an impact assessment category. Other selected inventory results were also presented and discussed upon.

Interpretation phase

This phase is closely related to the inventory and impact assessment results, where the choice of the relevant data, and the way to present them becomes important. These results should be compared with the aim at the goal and scope phase, and only results which help in drawing conclusions and recommendations are presented. [40]

4.2 LCC Framework

LCC is a process of evaluating the overall costs involved in the life cycle of a particular product. It helps in creating a balance between the initial investment and the overall costs such as operation and maintenance costs of the product. There are basically three types of LCC, namely, conventional, environmental and societal LCCs.

The conventional LCC deals with the assessment of all monetary costs which are covered during the life cycle of a product. This assessment is only economic evaluation of the life cycle of the product under study. Usually, EOL costs are not considered during its evaluation.

Societal LCC deals with non-monetary aspects related to the effects on the society, which is of less relevance to this study.

Environmental LCC involves all the costs related to the product (similar to conventional LCC), adding to it the externalities that might be internalized in the near future. The framework of LCC is similar to that of the LCA, and thus the Goal and Scope should be the same as defined in LCA. A challenging issue here is when some costs are incurred by different actors, like the case of a producer and the user. In this case, it is important to avoid double counting when both parties incur the cost (for example the price of the product from a user perspective is already accounted for in the production of the product from a producer perspective). To solve this, a good approach is using the polluter pays principle. In the case of the gearbox, the producer is the polluter when manufacturing the gearbox, so the cost should be from the producer's perspective at that stage. The user will incur the usage face when he is the polluter then.

The collection of the data might also be inconsistent from different providers, and some data could be business sensitive. Other data could also require future prices that require to be discounted to present value, thus it is important to be as consistent as possible.

The impact assessment phase is omitted in the LCC, because all the data already have a common unit (currency) that can be easily compared. Interpretation and communication phase, however, follows the same terminology as LCA [41].

In this study, conventional LCC has been applied, including the EOL phase.

4.3 OpenLCA and ecoinvent

The OpenLCA software for LCA calculations started as a project idea in 2006 by GreenDelta, with the aim to design and develop a high speed framework for sustainability assessment and life cycle modelling. The software allows visually appealing and ease in modelling both simple and complicated models. Being an open source software, it allows developers to improve it or add to its functions. OpenLCA version 1.5 has been used in the study for modelling purpose. The most important part in the modelling is the data-set used, where the choice of the software becomes of less relevance. The database used in the study was ecoinvent version 3.1. [42]

5
LCA and LCC

5.1 Goal and Scope Definition

5.1.1 Goal and Context

In an effort to shift the Swedish manufacturing industry towards a more circular economy model, the research program Mistra REES - Resource efficient and Effective Solutions based on circular economy thinking- would like to know the best product design for REES. The purpose of this study is to investigate which of the two spare-part gearbox production alternatives, manufacturing from raw materials or remanufacturing from used parts, has the least environmental and economic impacts. Besides, the study will examine which activities in the life cycle of a manufactured gearbox have the highest environmental impact and which are the costliest.

The results of this study will be used by Mistra REES in a wider perspective, integrating them with business models and policies for REES studies to better understand the circular economy thinking. They will also help in future strategies at VCC design, making more remanufacturing-friendly cars. The hot-spot analysis will help STS improve its sustainability standing and profitability by focusing on few activities with highest impacts.

5.1.2 Scope and Modelling Requirements

The scope of the study consist of different processes from raw material extraction to the manufacturing and remanufacturing stages. The use phase will be modeled with the fuel consumption only. The collection phase will be included in the remanufacturing case. For the end-of-life, the cut-off method will be used for materials recycled in open loops to other kinds of products. The energy needed for the recycling will be considered, whereas no credit will be given to the system for recycled materials.

The LCA that will be done is an attributional LCA.

Functional Unit
The study focuses on two methods of production of the gearbox. The gearbox understudy will be used as a spare part, whether it was new or remanufactured. The function of the gearbox is to control the output of the engine depending on its speed, regardless of its weight or size. In other words, it is used to drive the car for a specific distance. As an average, a distance of 250,000 km is assumed as a lifetime after replacement, which will mainly concern the use phase. Thus, the functional unit in this study will be one 6-speed gearbox used for 250,000 km.

Result Presentation
The main interest for manufacturers is to abide with the policies regarding emissions, and try to save resources. Accordingly, the results are presented as Regulated Emissions and Resources.

The regulated emissions include nitrogen oxides, hydrocarbons, carbon monoxide, carbon dioxide, and particles under 2.5µm. For the resources, it includes the use of fuel (fossil fuels and renewables) and materials (mainly ores).

Emissions contributing to climate change have in addition been aggregated to Global Warming Potential (GWP). GWP is an important factor when it comes to the automotive industry, because it is easier to understand the effects based on a CO_2-equivalents value. United Nations International Panel on Climate Change (IPCC 2013) characterization factors are used for GWP for 100 years.

System Boundaries: Natural System
The cradle of the system is the extraction of the raw materials, and in the remanufacturing system it will also include collected used gearboxes (collected after going to maintenance and not after end-of-life). The environmental impact and cost analysis of building the factories and the machines used will not be included in the study. The transportation of raw materials to manufacturing facilities is also omitted. The end of the system is recycling (energy used for it) as discussed earlier, where the use of the recycled material is omitted. The natural system boundaries can be seen in the initial flow chart (Figure 5.1) represented by the dashed lines.

System Boundaries: Geographical
The origin of extraction of the raw materials will be modelled using available models, which are generic for non European countries. The manufacturing facility is in Japan, and the remanufacturing one is in Sweden, thus production activities will be modeled accordingly regarding energy sources. The use phase will be only in Sweden, and hence European data will be used for that.

System Boundaries: Time Horizon
VCC promises its customers that they will always provide spare parts for their cars for 15 years after end of production. The replacement of the gearbox might take place after 5-10 years, if it happens. Thus, the time frame of this study will be the next 15 years. Since we are using attributional LCA, the used data will be based

on the present manufacturing/remanufacturing process.

Allocation
In the remanufacturing process, since the material used is mostly recollected, 0% of the extraction is allocated to it. This means remanufacturing will not carry any burden of extraction of raw materials. Raw material extraction and production will only be accounted for in the manufacturing of a new gearbox. For the recycling of the scrap after a remanufactured gearbox is used, the system is not credited with avoided need of raw material.

Initial Flow Chart
Figure 5.1 shows the initial flow chart for the manufacturing system and the remanufacturing one. The following flowchart is a general one showcasing the main processes for the production, but a more detailed one has been illustrated in the inventory analysis.

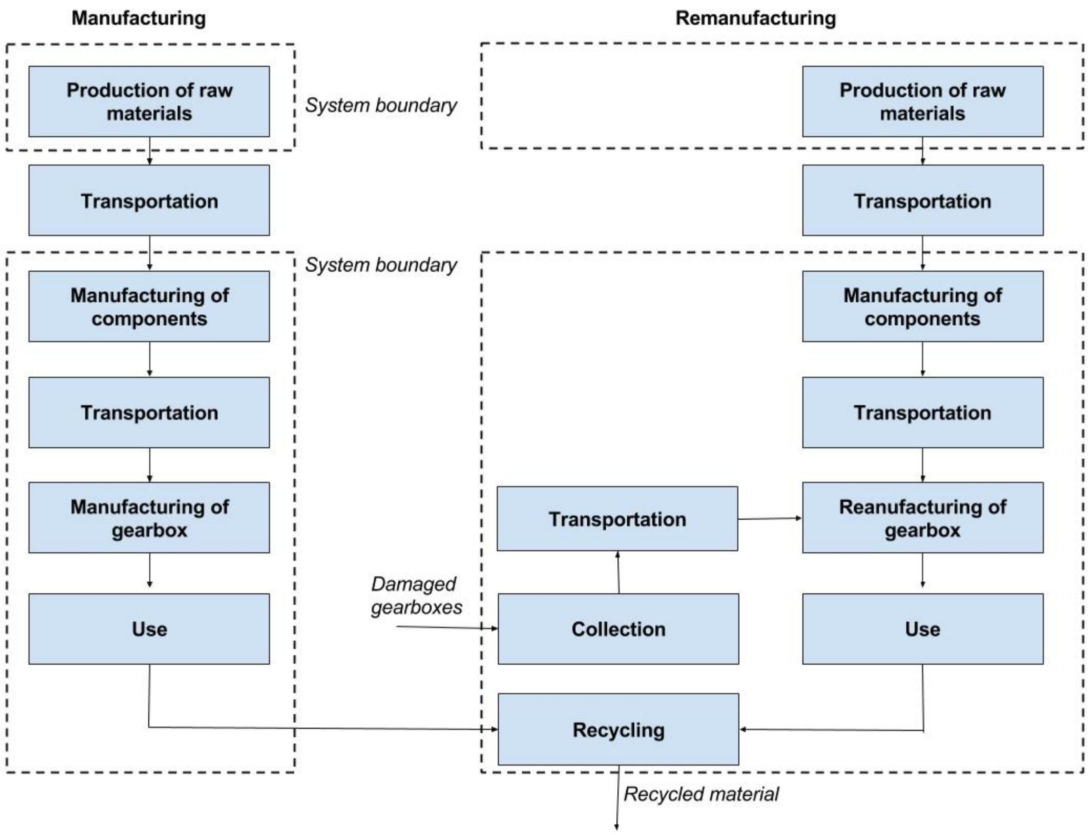

Figure 5.1: Initial flow chart showing the life cycle and natural boundaries of both new and remanufactured gearbox.

Assumptions and Limitations
The following assumptions have been made through the LCA:

- A remanufactured gearbox is 3% more efficient than a manufactured one. This

is due to shifting to the new generation of technology in remanufactued gearboxes, which will be discussed later.
- All collected gearboxes have the same quality, and thus require the same treatment at the remanufacturing facility.
- A gearbox is remanufactured once and then sent to scrap.
- All the road transports (Between Belgium, the Netherlands, and Sweden) are assumed to take place with 7.5-15 ton, EURO 5 lorry, while for the sea transport (From Japan to the Netherlands), it is assumed to be with a transoceanic ship.
- VCC credits points to dealers when receiving the damaged gearboxes. Due to the complication of the points system, it is assumed that damaged gearboxes are received for free.
- The transportation of raw materials was not included in the system boundaries due to the lack of information from the manufacturing plant.

Data Quality and Collection
Data about the composition of a gearbox (weights and material) has been collected from Volvo Cars through IMDS. Thus this data is relevant and reliable (but only accessible for Volvo Cars). This data was linked to the ecoinvent database to get the input and output flows. Similarly, data for the remanufacturing of the gearbox (injection rates, weights, material and energy use, and transportation distances) has been collected from STS, therefore it has the same characteristics. Other data was collected through interview with relevant employees, and numbers were given as rough estimations. Any data that could not be accessed, assumptions were made based on other LCA studies and available databases (e.g. ecoinvent), usually ones related to the automotive industry and representing Sweden or Europe.

5.2 Inventory Analysis

5.2.1 Inventory Analysis: Manufacturing

The modelling of the manufacturing system will consist of the upstream level (extraction and production of raw materials), production level (production of the components and the assembly), transportation involved, use phase, and the end-of-life level. From hundreds of parts and components comprising the gearbox, 30 parts were chosen carefully which constituted to around 93% of the total weight of the gearbox. The other components are mainly small bolts, bearings, shims, seals, sensors and screws which could be estimated as steel. Figure 5.2 shows the assembly structure, with various sub-assembly processes, and parts in each process. Only parts which are used in the study are shown in the figure.

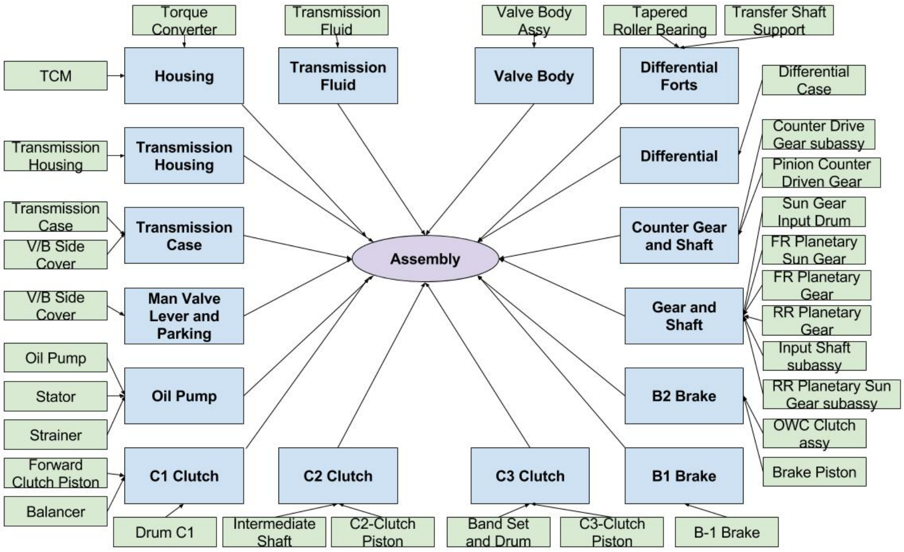

Figure 5.2: Gearbox Assembly Structure with sub-assembly processes and parts.

For the upstream material extraction and production, and the mechanical process used to form the parts and components, the ecoinvent 3.1 database was used. The main input to these processes are the ores, together with heat and electricity from various technologies, and the output is different emissions. Energy data for the final assembly of the gearbox is taken from STS, and assumed to be the same as that at AW Japan, by changing the country from Sweden to Japan in ecoinvent. Thus, this process has minor effect compared to the upstream processes.

The weighing of the parts was physically done at STS workshop, and the material composition of them has been taken according to different VDA classifications from International Material Data System (IMDS). A detailed graph of different materials for each VDA classification could be found in Appendix A. The majority of the materials have been found to be from classification 1 (Steels and Iron Materials) and 2.1 (Aluminum and Aluminum Alloys). Due to the confidentiality agreement, this data cannot be shown.

The transportation of the raw materials from the extraction sites to the production facilities is not included. This is due to the large uncertainty in the location of these extraction sites. Thus, the transportation only includes sea transportation by ship from Japan to Belgium, then road transportation with trucks from Belgium to Sweden.

The fuel consumption used for the use phase is according to the Extra Urban Driving Cycle (EUDC). The total duration of the EUDC is 400 seconds with a distance of around 7 Km, at an average speed of 62.6 km/h [43]. The allocation of the emissions of the whole car to the gearbox is assumed to be 5% due to friction losses. These losses include viscous losses (in the oil tank, gear contacts, synchronisers, and bearings), friction in gears, friction in bearings, and friction in seals [44]. The assumed distance driven through the studied life cycle (20 years) is 250,000 km, and the car used is a EURO 5 diesel engine car.

According to [45], it could be assumed that 90% of the parts of the car is recycled and 10% ends up in landfills. However, since the gearbox is mainly made of metals, it has been assumed in this study that 100% of the gearbox is recycled. Also, some times part of the existing gearbox is collected for remanufacturing instead of recycling at the EOL, but this accounts for less than 1% of the existing gearboxes. This is only done in extreme cases when no spare part could be secured from collected damaged gearboxes or newly manufactured ones. Thus, this portion has not been accounted for in the model. It is to be noted that the main source for remanufactured gearboxes is damaged gearboxes collected at maintenance facilities and not gearboxes collected at EOL!

For the modelling of the recycling, only the energy used in the recycling facilities has been taken into account. In the case of aluminum, this includes refining in rotary and reverberatory furnaces, alloying, and casting to secondary billets. Similarly for steel, energy needed for melting has been considered.

A more detailed flow chart for the manufacturing system is shown in figure 5.3, which is used as a base to draw the model in OpenLCA. Since there are many components in the model, most components have been grouped in 6 groups consisting of common raw materials, as shown in 5.1. The assumed manufacturing process for steel components is milling and drilling, while for aluminum is only die casting.

Group number	Components included
1	Torque Converter | Intermediate Shaft | C-2 Clutch Piston
2	T/A Housing | Transaxle Case | First Reverse Brake | Piston Valve Body
3	Transaxle Side Cover | Oil Pump | Forward Clutch Piston | Clutch Balancer | C3 Clutch Piston | One Way Clutch | Sun Gear Input Drum | Others
4	M/V Lever | FR Planetary Sun Gear | RR Planetary Gear | Tapered Roller Bearing | Transfer Shaft Support
5	C-1 Drum | FR Planetary Gear
6	Brake Drum Band Set | RR Planetary Gear | Counter Drive Gear | Pinion Counter Driven Gear | Differential Gear

Table 5.1: Components grouped according to common raw materials used

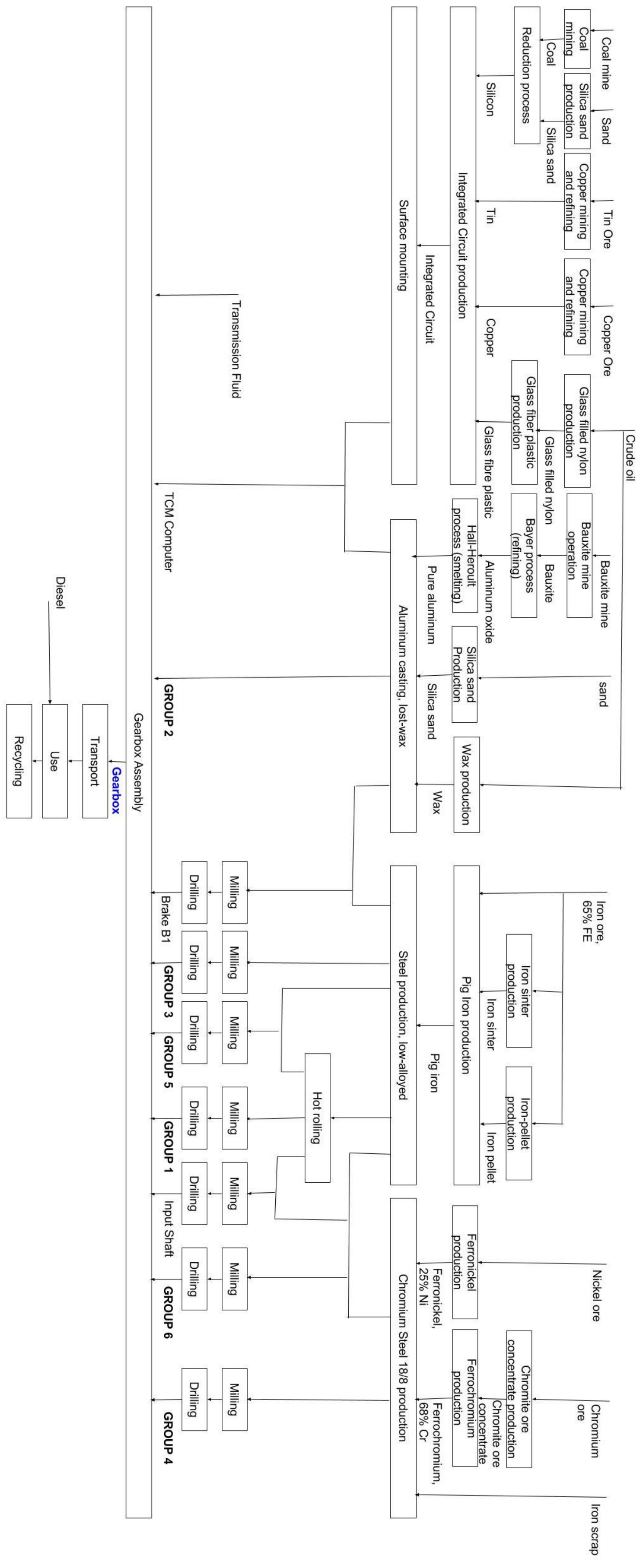

Figure 5.3: Flow chart of the manufacturing system.

5.2.2 Inventory Analysis: Remanufacturing

The modelling of the remanufacturing system is almost the same as the manufacturing one, with the main difference being in the injection rate of the material. The injection rate is the rate at which new material is used in the remanufactured modelled. This confidential data has been provided by STS.

The other difference between the systems is the transportation that takes place before and after remanufacturing. The new spare parts come from Japan to STS (Stenungsund) through Maastricht, The Netherlands (similar to the previous case, but with less weight). The used cores are damaged gearboxes collected from various service centers in Sweden and sent to Arendal, then to Maastricht for storage, then sent back to STS whenever needed. The remanufactured gearboxes are then sent to VCC at Torslanda. Detailed information about the different trips is shown in Appendix C.

The use phase here has also been assumed to be more efficient than the newly manufactured gearbox. This is mainly due to the development of a new generation of the gearbox by the time the old one is replaced. According to Mikael Nilaens from Volvo Cars, a new generation for the gearbox reduced fuel consumption by 3%, which can be applied to the remanufactured ones. The improvements were done by altering oil and the use of less friction material (with bolts and valve body). These improvements can also be applied to the newly manufactured gearboxes, but in this study, it is assumed that those which are already manufactured, stay in storage for around 2 years before the new generation ones arrive. For the remanufactured; however, it is directly applied. Thus, a 3% reduction in the use phase was only taken in the remanufacturing case. The flow chart for the remanufacturing system is shown in figure 5.4

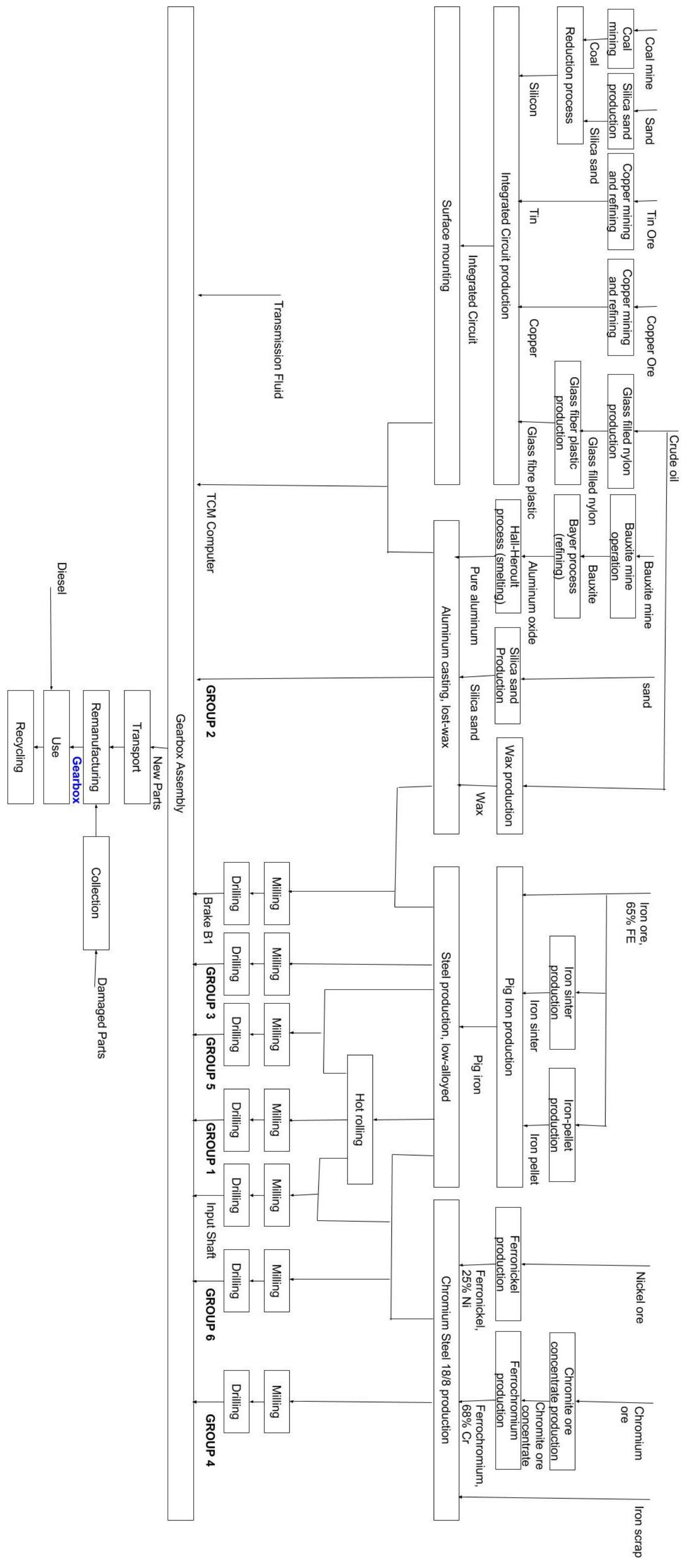

Figure 5.4: Flow chart of the remanufacturing system.

5.3 Life Cycle Cost

In the case of the gearbox, the life cycle cost could be calculated as material and production costs and use phase and EOL costs. Material and production costs include the cost involved in manufacturing and transportation. The advantage of conducting this analysis is to evaluate how much savings could be achieved by using a remanufactured gearbox as a spare part, during its whole life cycle. For the use phase and EOL costs, the capital cost of the gearbox is not considered to avoid double counting. The differences; however, occur at the operating cost (mainly fuel cost). For the user, there are additional costs like the maintenance cost (which is emitted here) and the recycling profit, but this is indifferent for which gearbox is used. Finally, no discounting has been done for the fuel prices and the recycling profit due to lack of time.

5.3.1 Material and Production Costs

Following the flow charts for both manufacturing and remanufacturing of the gearbox, this stage includes the raw material phase, manufacturing phase, and transportation phase. In the raw material phase, prices of the materials have been taken based on spot market, due to the confidentiality of prices use by VCC. The three main materials used are aluminum, steel, and chromium steel. Table 5.2 shows the various prices of the different metals based on the spot market [46] [47] [48].

Material	Price (SEK/kg)
Aluminium	18.67
Steel	0.91
Chromium steel	19.86

Table 5.2: Prices for each material based on spot market price.

Material cost will be calculated using the following formula:

$$Material\ cost\ (SEK)\ =\ Price\ of\ raw\ material\ (SEK/kg) * amount\ of\ raw\ material\ (kg)$$

For the manufacturing/remanufacturing phase, electricity prices and labour costs have been considered according to the Swedish and Japanese numbers as shown in Table 5.3 and Table 5.4. The Japanese data is used for manufacturing, and the Swedish for remanufacturing.

Country	Labour cost (SEK/hr)	No. of hours
Japan	117	8
Sweden	190	5

Table 5.3: Labour costs for each country.

Country	Elect. cost (SEK/kWh)	Elect. consumption (kWh)
Japan	1.55	74.04
Sweden	0.84	74.07

Table 5.4: Electricity costs for each country.

The labour cost is according to skilled labour rates provided by Volvo. The conversion rate from 1 Japanese Yen to 1 Swedish Krona has been taken to be 0.078 SEK/JPY [49].
It has been estimated that each gearbox needs 8 hours to be manufactured. For remanufacturing, however; it takes 5 hours according to information given by STS. Regarding electricity, information about the Swedish data was provided from STS also. The Japanese data has been taken from the Energy Information Administration [50], while the consumption was assumed as the same.

Labour costs have been calculated using the following formula:

$Labour\,cost\ (SEK)\ =\ Labour\,rates\,per\,working\,hour\ (SEK/hr) * Number\ of\ working\ hours\ (hrs)$

and electricity cost has been calculated according to the following formula:

$Electricity\,cost\ (SEK)\ =\ electricity\,price\ (SEK/KWh) * electricity\,consumed\ (KWh)$

Table 5.5 shows the various transportation costs involved in transporting the gearbox. The cost for sea transport has been obtained from Maersk Line in Japan, based on general quote provided by the company. The cost for road transportation has been estimated based on values provided by a local shipping company in a study [51].

	Mode of Transportation	Cost/ (kg*km)
Japan	Sea	72
Europe	Road	1087

Table 5.5: Transportation costs for Japan and Europe

Therefore, total LCC from material and production will been calculated as:

$LCC\ material\ and\,production\ =\ Material\ cost + Labour\ cost + Electricity\ cost + Transportation\ cost.$ [52]

5.3.2 Use Phase and EOL Cost

In the use phase, the fuel used in the cars has been assumed to be standard diesel with the spot market price in Sweden equivalent to 17,58 SEK/litre [53]. It is also assumed that the car drives 250,000 km, the fuel consumption is 6.8 L/km, and that the gearbox contributes to 5% of these losses, thus the formula for the use phase cost will be:

$Use\,cost\ =\ fuel\,price\ (SEK/L) * fuel\ consumption\ (Km/L) * distance\,traveled\ (km) *$ $gearbox\ physical\ contribution\ (\%).$

Other costs such as repair and maintenance, license and insurance costs have been omitted in this study.

The final cost is the EOL cost, which is the cost for recycling. It might be thought that there should be a profit to the user selling his car to scrap companies (salvage value), but this would contradict with the scope of the LCC. When the user sells the car, no environmental damage is done, and thus it has not been counted. It might also be considered a profit since recycled material will be used in other fields as reduced raw materials, but this is also outside the system boundaries of this study. A consumer pays 45 Euros as recycling fees when purchasing a car. This fee ensures vehicle dismantling, collection, recycling, and shredding [54]. The gearbox usually accounts for 5% of the weight of the cars, (Volvo V60, a typical vehicle that uses the gearbox AWF-21, weighs around 1,900 kg, and the gearbox itself weighs around 95 kg according to information from VCC). Accordingly, the use phase and EOL cost is calculated as:

$EOL\ cost\ =\ recycling\ cost\ (SEK/vehicle)\ *\ gearbox\ weight\ contribution\ (\%).$

Therefore the cost of the use phase and EOL have been calculated as:

$LCC\ use\ and\ eol\ =\ Use\ cost\ +\ EOL\ cost.$ [52]

6
LCA Results

6.1 Manufacturing and Remanufacturing Scenario

In the automotive industry, the most relevant inventory data is those related to the regulated emissions in the EURO standards. The regulated emissions include nitrogen oxides, hydrocarbons, carbon monoxide, carbon dioxide, and particles under 2.5 µm. Figure 6.1 shows the emissions of regulated substances over the life cycle normalized with respect to a newly manufactured gearbox. Exact values cannot be shown due to confidentiality reasons. As it can be seen, a remanufactured gearbox has 20-50% less emissions than a manufactured one for all regulated emissions.

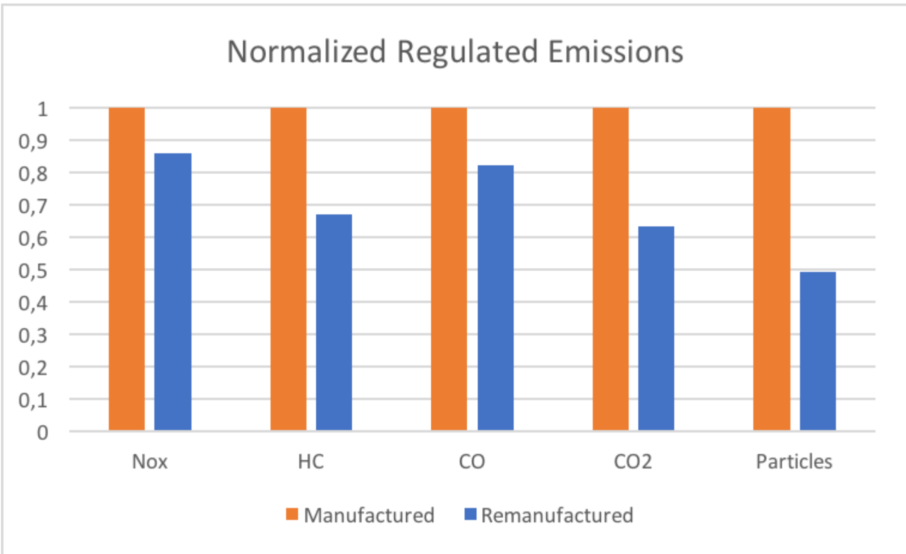

Figure 6.1: Normalized regulated emissions from manufactured and remanufactured gearbox over the whole life cycle.

The main contributor to these emissions is the use phase during the combustion of diesel. For the NOx emissions for example, around 90% of the emissions where due to the use phase, where the remaining where equally distributed between steel and aluminum production. Looking at the Hydrocarbons, the major emissions are aromatic hydrocarbons to the surface of water. Here, the main contributor is the aluminum production, with around 80% of these emissions. For the carbon monoxide emissions, it is also highly dominated by the use phase (around 95%), but the remaining emissions are mainly due to milling and drilling (manufacturing processes).

This would give remanufacturing a higher advantage if reuse rates are increased.

Another interesting observation is that the carbon dioxide emissions are less dependant on the use phase (40%), with around 12% coming from transportation of the gearbox (both in sea and on land). This would play a major role in deciding on the optimal collection distance for reusing.

Since the main concern of the study is observing the benefits of remanufacturing, figure 6.2 shows the normalized emissions excluding the use phase, which is only 3% better for a remanufactured one while it has the highest emissions. Even lower emissions are seen due to the same reasons discussed before.

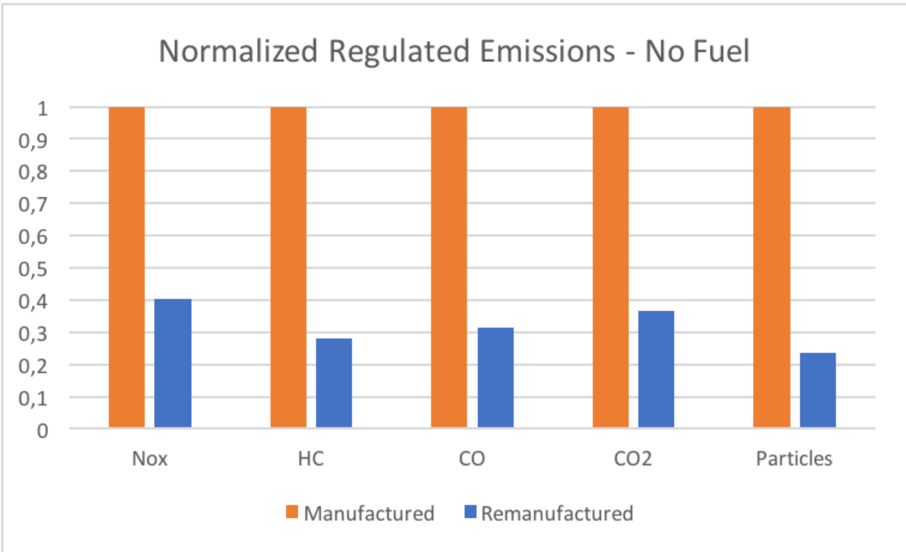

Figure 6.2: Normalized regulated emissions from manufactured and remanufactured gearbox, excluding the use phase, over the life cycle.

A main advantage of using a remanufactured gearbox is that less raw material is needed. With more metals becoming scarce day after day, it is important to have a look at the consumption of raw material from the ground. Only materials weighing more than 5 kg are shown, and they are normalized with respect to a newly manufactured gearbox. Calcium carbonate and gravel had the highest weights, which are mainly used in the Aluminum production and casting and in the use phase (production of the diesel). Graph 6.3 shows the comparative normalized results.

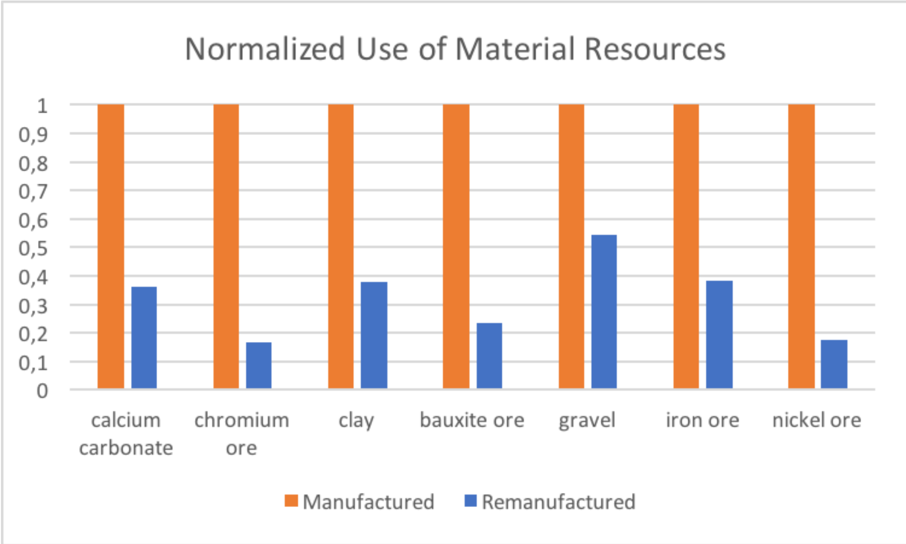

Figure 6.3: Normalized use of material resources in manufactured and remanufactured gearbox over the whole life cycle.

For all materials, remanufacturing saves between 50-80% in raw materials (based on the current injection rates). The main materials used in the gearbox are steel (hot rolled and chromium) and aluminum. The bauxite and clay are mainly used in the aluminum production, which is used in the production of transaxle case, transmission housing, and valve body. The iron ore, chromium ore, and nickel ore are mainly used in the production of steel and chromium alloys. The major parts using these materials are torque converter, differential gear, RR planetary gear, and the oil pump.

In addition to the material resources, it is important to study the energy resources. This is important not only from the environmental point of view, but also from the security of supply point of view. Figure 6.4 shows the Energy consumption (normalized with respect to a newly manufactured gearbox) based on different energy resources. Since the information was given in weights and volume, the following heat values where used: 23,9 MJ/kg for coal, 38 MJ/m^3 for natural gas, and 42 MJ/kg for crude oil [55].

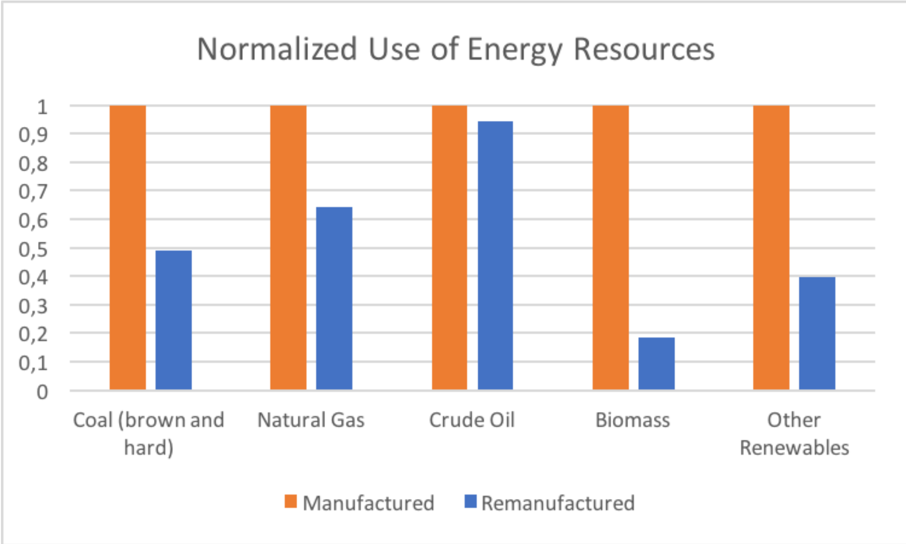

Figure 6.4: Use of different energy resources in manufactured and remanufactured gearbox over the whole life cycle.

Crude oil looks like the highest contributor, but that is due to the fact that most of it (around 93%) is in the use phase. Natural gas is also dominated by the use phase (50%). Coal, on the other hand, is mainly used in the steel production (50%) and biomass in the Aluminum production (70%).

If we exclude the use phase again in this context, the aggregated energy use coming from the stated resources is reduced by 62.1% in a remanufactured gearbox compared to a newly manufactured one.

Another important figure to analyze is the equivalence of CO_2 emissions during the lifetime of the gearbox. This illustrates the carbon footprint of the product. For this purpose, characterization using the IPCC 2013 will be performed in the coming analyses. Global Warming Potential for 100 years is presented in terms of kg CO_2-equivalence.

Figure 6.5 shows the contribution of each phase in the life cycle of the gearbox to the emissions of CO_2 equivalence. Again, values are normalized with respect to a newly manufactured gearbox. It is clear that the use phase has a huge share of the emissions. However, for the newly manufactured gearbox, the extraction of raw materials accounts to 42%, compared to 41% in the use phase. In the remanufactured case, the use phase accounts for 63% of the emissions. As a cumulative result, remanufacturing reduces CO_2-equivalent emissions by 37%.

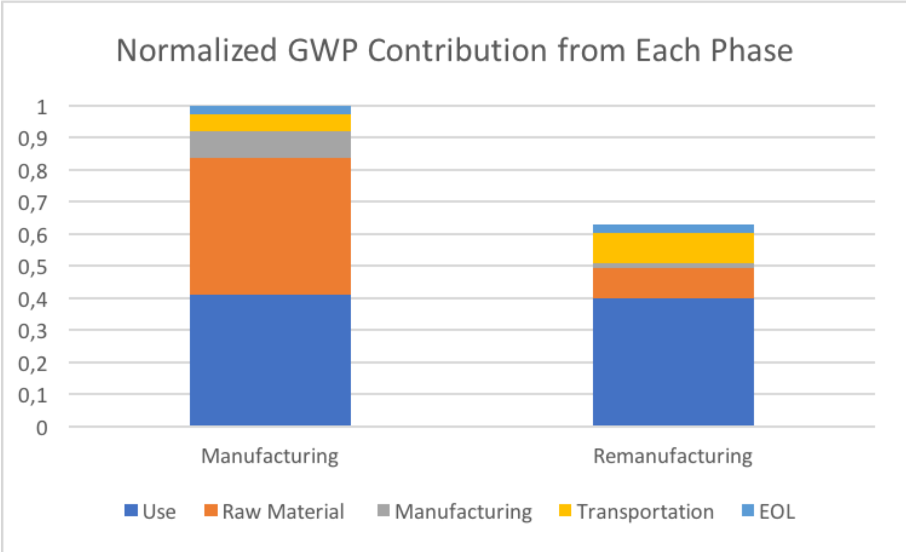

Figure 6.5: Normalized regulated emissions from different phases of the manufactured and remanufactured gearbox.

Using the same analogy as before, graph 6.6 shows the same results without the use and recycling phase. A closer look here shows that although emissions from extraction of raw materials and manufacturing is decreased with remanufacturing, the emissions from transportation increases. The reason here is that transportation only includes that of the new gearbox, the used gearbox, and the collection distance. It does not include the transportation of the raw materials from the ores to the production site, which will contribute to higher emissions due to far distances and heavier raw materials. Excluding the use and recycling phase, remanufacturing reduces CO_2-equivalent emissions by 64%.

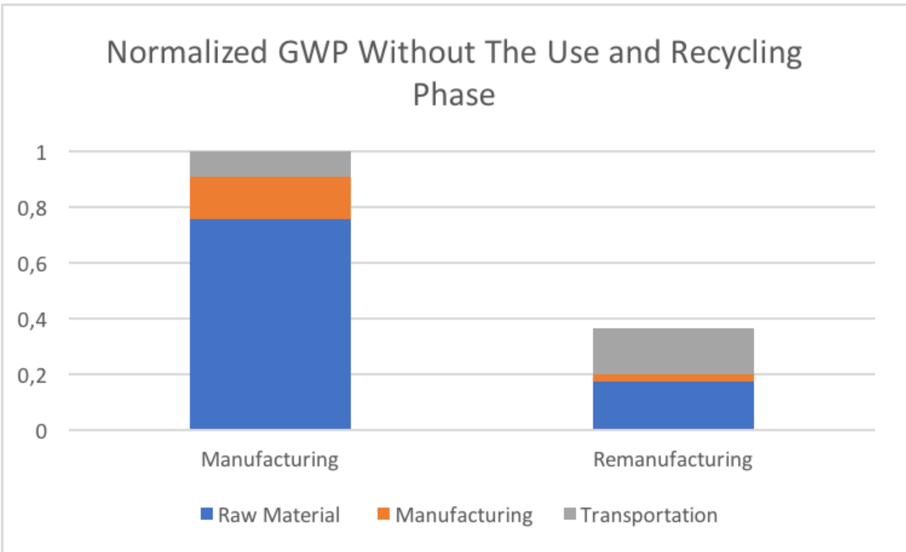

Figure 6.6: Contribution of different phases towards Global Warming Potential without the use and recycling phase.

A detail look into different phases in Figure 6.7 shows the normalized CO_2-eq emissions from process having at leaast 5 kg CO_2-equivalence. In the transportation phase, it is clear that remanufacturing reduces the need for long sea transports but on the other hand increase the demand for land transport in order to collect the gearboxes from the users and deliver them to STS. Despite the fact that electricity consumption has been assumed the same for the assembly and other handling processes for both gearboxes, the emissions from a newly manufactured gearbox are much higher than those of a remanufactured one. This is because in the first case, the electricity mix taken is the Japanese, which is currently dominated by fossil, whereas in the other, the electricity mix is the Swedish (dominated by clean energy). This assumption may not be very accurate, because according to the AW's Sustainability Report, the company uses clean energy and a lot of energy saving measures, but due to confidentiality the exact information could not be made available. Nevertheless, because electricity accounts for less than 1% of the emissions, it does not affect the overall results.

Different components differ a lot according to their different injection rates. Transmission Control Module(TCM) for example has an injection rate of 100% and thus having the same contribution in both cases, while transmission housing has an injection rate close to 1% and has much lower contribution when remanufactured. The positive interpretation of this is that the heaviest parts with the most aluminum and steel compositions have relatively low injection rates, giving a big advantage for remanufacturing.

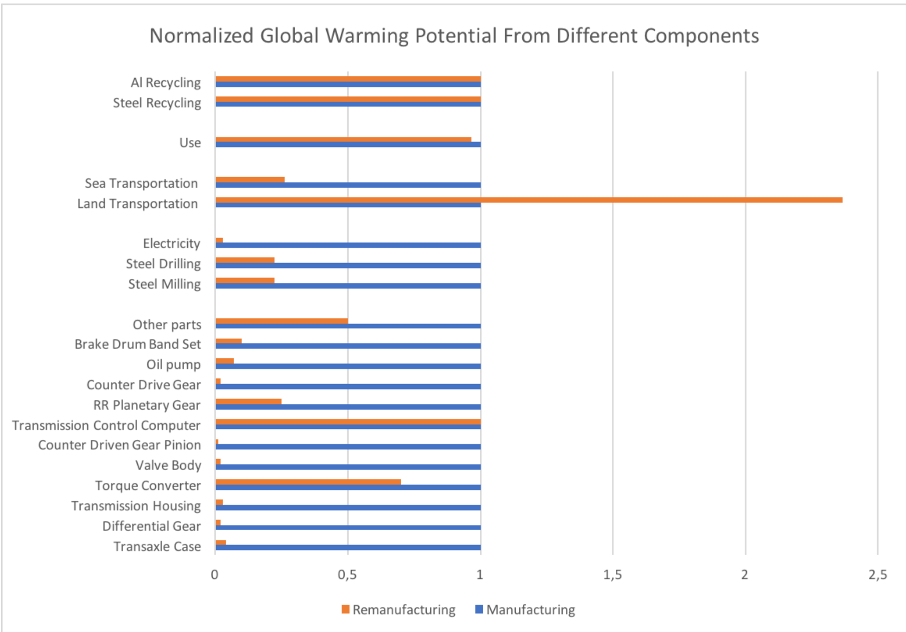

Figure 6.7: A comparison of contribution of each process or component towards Global Warming Potential, normalized with respect to a newly manufactured gearbox.

6.2 Sensitivity Analysis - Injection Rates

As seen from the previous section, injection rates play a major role in environmental impacts during the life cycle. A sensitivity analysis has been done using three cases: 0%, 50%, and 100% injection rates. IPCC 2013 has also been used for this purpose. The 0% case seems unrealistic, because some parts (TCM for example) have to be replaced entirely, which is not the case. Graph 6.8 shows how increasing the injection rate plays a role in increasing the global warming potential. It is to be noted that it is not a linear graph, because other factors also play a role (use phase and transportation distances).

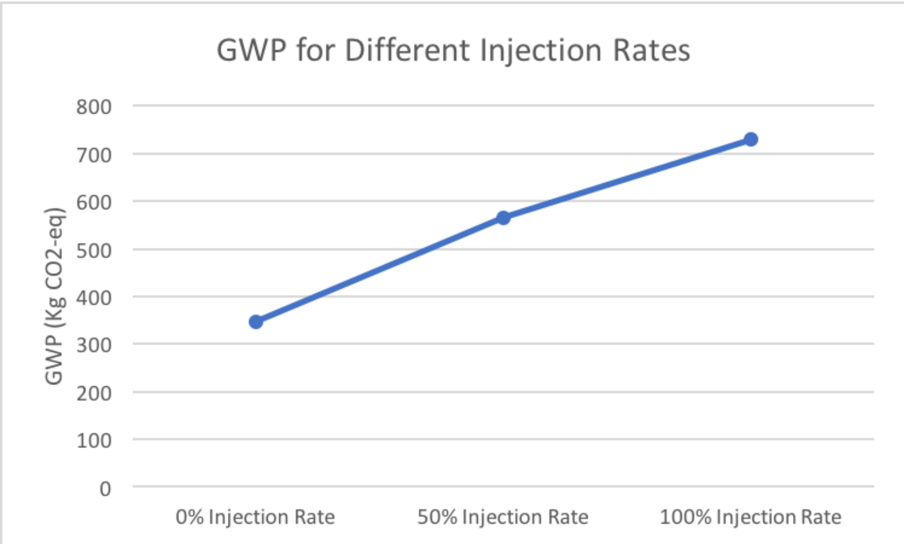

Figure 6.8: Effect on Global Warming Potential for different injection rates.

6.3 Sensitivity Analysis - Transportation Distance

The biggest advantage of remanufacturing is that less raw materials are needed for the production, thus it incurs fewer emissions. However, this comes with a price, which is the emissions from the added transportation due to the collection of the used parts. A sensitivity analysis has been done to know at what collection distance would it be better to manufacture a gearbox from raw materials instead of remanufacturing of collected parts.

To calculate the distance where collecting the parts would have a worse outcome than manufacturing new parts, the difference in GWP between the two scenarios is considered. This difference should come from the road transportation in collecting these parts. The difference is around 269 kg CO_2-eq. Besides, the model used in OpenLCA for the road transport emits around 4.94217 kg CO_2-eq/ton.km. Knowing that the collected gearbox weighs around 95 kg, the additional distance which generates 269 kg CO_2-eq would be 13,958 km. The current collection distance from around Sweden to Arendal is assumed to be 500 km, thus the new collection distance must be 14,458 km.

In order to understand the results, the distance from the north to the south of Sweden is 1,572 km, and the distance from Abisko (north of Sweden) to Gibraltar (South of Spain) is 5,200 km. Thus, wherever the collection point in Sweden is, and wherever in Europe the gearbox is coming from (although our boundary for the use phase is only Sweden), it will always be better to remanufacture than to newly manufacture a gearbox.

6.4 EOL Collection with Remanufacturing Scenario

It is always debated that the collection is the hardest part in a circular economy model. For Volvo, the collected parts are the ones received during maintenance, so it is quite easy to get them. However, at the end of life of the vehicle, it is always sent for shredding and scrapped as a whole, thus incurring some emissions due to the recycling process. As an alternative EOL option, collection of the gearboxes before shredding could be done. Figure 6.9 shows how the loop could be closed when the end of life is replaced with collection instead of recycling (dashed lines show how it was in the initial flow chart).

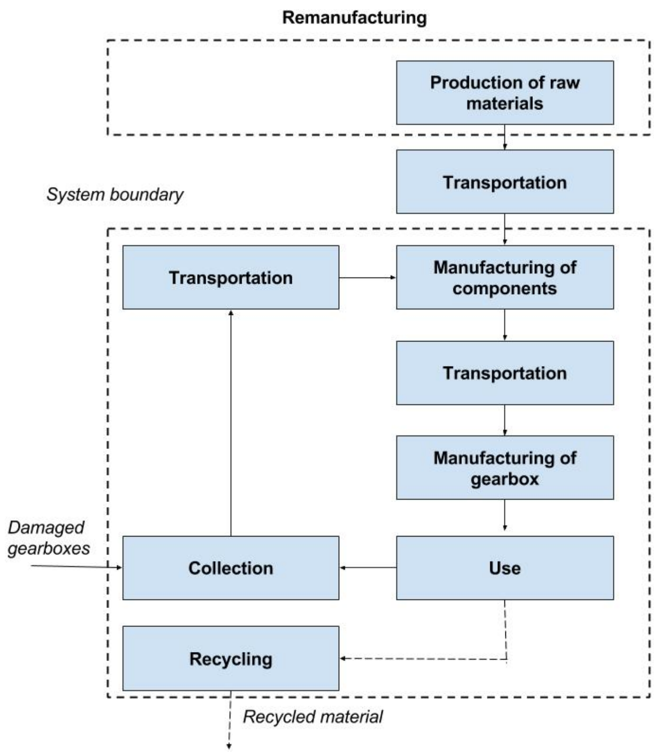

Figure 6.9: Flowchart for End Of Life collection with Remanufacturing Scenario

Since collected parts are already modelled in the previous system, this will only give an advantage in the EOL phase. Thus the result will only be a reduction of about 5% of GWP. This can be seen in the previous figure 6.5, where the EOL is removed. To have more accurate figures, and to benefit more from this stage, the system boundary should be expanded to include the collected spare parts, then it becomes more comparable.

7
LCC Results

According to an interview conducted with Nils Eriksson from Volvo Cars, a replacement part costs around 2,000 SEK, so this will be a basis to make sure that the LCC is within the limits. The cost of material and production should in fact be a lower figure to make sure that the company makes a profit. Based on the used resources, the material and production cost for a newly manufactured gearbox exceeds that number, but is still within the range. The reason is that the company get better fares when buying in bulk, but this does not affect the comparison, since same prices are used for both cases. Based on the formulas and data presented in section 5.3, table 7.1 summarizes different costs according to different life cycle phases.

Life Cycle Phase	Cost Type	Man Cost	Reman Cost
Raw Material	Material	840	80
Manufacturing	Labour	940	950
	Electricity	120	60
Transportation	Transportation	300	560
Total Man. Costs		2200	1650
Use	Fuel	15,000	14,500
EOL	Recycling	10	10
Total Use and EOL Costs		15,010	14,510
Total LCC (SEK/gearbox)		17,210	16,160

Table 7.1: Cost Summary

Looking at the contribution from each phase to the LCC, it is clear that the use phase is the dominant phase again. The EOL phase, on the other hand, has a very low contribution. Accordingly, Figure 7.1 shows the contribution of the other phase to the total LCC. In the newly manufactured gearbox, the cost is highly dominated by manufacturing cost and raw material cost. In the remanufactured case, the transport cost becomes of relevance, accounting for around 35% of the total cost of the gearbox, whereas the raw material cost becomes close to negligible.

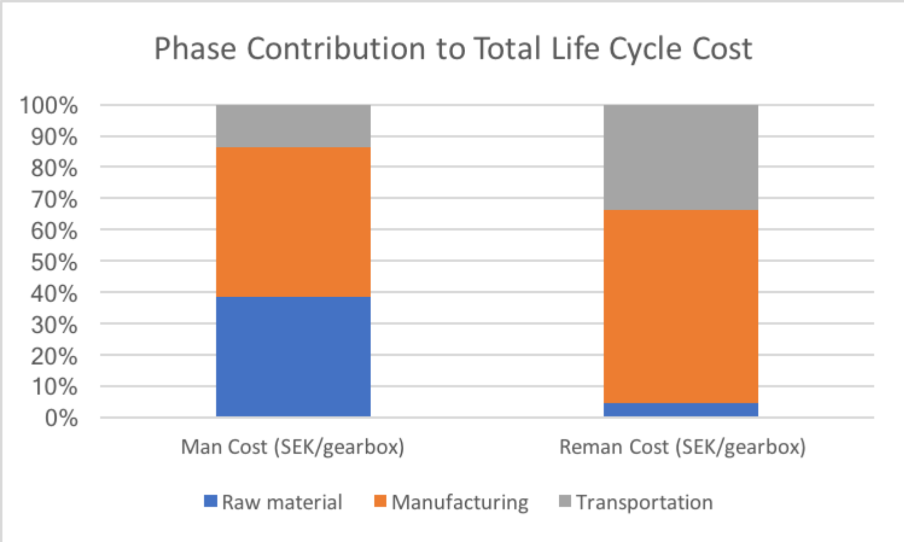

Figure 7.1: Comparison of costs for different phases, excluding the use phase, in manufactured and remanufactured gearbox

The total cost reduction when using a remanufactured gearbox is found to be 5%, but when the use and EOL are not taken into account, this figure becomes 25%. Figure 7.2 show the LCC results of each phase, excluding the use and EOL, normalized with respect to the newly manufactured gearbox costs. The greatest reduction (around 90%) comes from the raw material phase, where less material is needed for the remanufactured gearbox. The transport phase, however; increases by around 85%, but the total cost is still compensated for as an overall. The manufacturing phase seems to be the same, and this is mainly due to the higher labour costs in Sweden, which compensates for lower working hours.

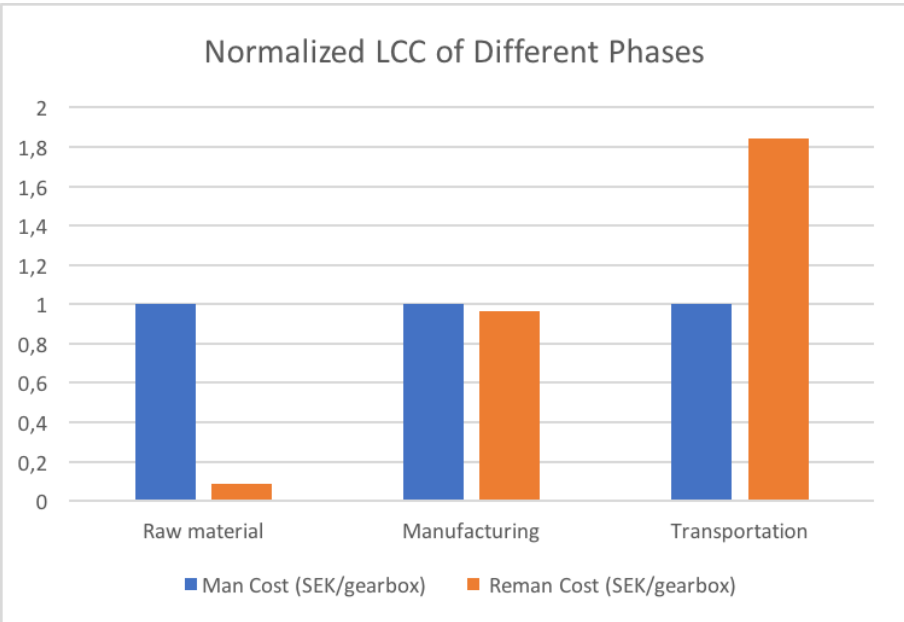

Figure 7.2: Normalized costs for manufactured and remanufactured gearbox

8

Conclusion and Recommendation

Based on the conducted LCA study and the chosen inventory parameters, remanufacturing seems to be a better environmental option when it comes to spare parts as it reduces the regulated emissions during the whole life cycle, and requires less material and energy resources. The global warming potential (measured in kg CO_2-eq) has shown a decrease by 36% according to the IPCC 2013 impact assessment method.

The results are highly dependant on the injection rates used at the remanufacturing facility, and to some extent on the transportation required for the collection of the used parts. A sensitivity analysis on the injection rates has shown that moving from 100% to 0%, the injection rate would reduce the Global Warming Potential by half (where the other half is mainly due to the use phase). Another sensitivity analysis has been performed for transportation distance which shows that the trucks which collect used parts should travel a distance of 14 498 Km before remanufacturing loses its advantages. This distance is longer than any distance between two European countries, and thus seems as an unrealistic scenario.

The use phase accounts for the major emissions in the life cycle of a gearbox, and thus focusing on reducing losses during the use phase would have high impacts on the overall results. Another factor is that at the end of life, cars are sent for shredding as a whole, including the gearbox. Removing the gearbox at this stage will not only save some emissions because of the avoided recycling process, but would also increase the chance for more remanufactured products, and thus more material savings.

The LCC results confirm what has been concluded in the LCA study, i.e. a remanufactured component costs less than a newly manufactured one. The producer (Volvo Cars) will benefit from cheaper prices of collected used parts, whereas the user will only benefit from the lower losses in the use phase (less fuel consumption).

Therefore, it is recommended that VCC continues the use of remanufactured gearboxes as spare parts, and maybe widen the scope for remanufacturing by including it in new cars as well. Besides, more effort needs to be put in on trying to reduce the losses in the gearbox during the use phase, which will have both environmental and economical advantages. Also, it is important to investigate why the injection rates for some parts, the Transmission Control Module for example, are still nearly 100%.

A final suggestion would be to start collecting used gearboxes before being scrapped to ensure they will be remanufactured, and the security of supply always exists. This will also help in raising the percentage of remanufactured parts in spare parts at Volvo more than the current rate of 15%.

For future studies, it would be suggested to include each and every part with its specific injection rate, which could not be done due to time constraint. It would also be good to have more information about the manufacturing processes that take place in the manufacturing facilities in Japan and information on the origin of raw materials. Hence a better energy model would be available and a better transportation model would be present containing data on transportation of raw materials. Besides, it is important to investigate the transportation routes that the used cores undergo before being remanufactured. If some trips are found to have no value in the supply chain, removing them would reduce some environmental damages and cost. Another important aspect to be considered is the allocation of the gearbox during the use phase. However, due to time constraints, it has been assumed that around 5% of the fuel in the car is lost in the gearbox (according to a study), but a better model can indicate exactly how much fuel is lost. Regarding the LCC, a tax equivalent to carbon tax might be added in future studies on the CO_2-eq emissions (obtained from LCA). This will internalize these externalities, and make the conventional LCC an environmental one.

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A

Appendix A: VDA Classification

Number	Description
0	undefined
1	Steel and iron materials
1.1	Steels / cast steels / sintered steels
1.1.1	unalloyed, low alloyed
1.1.2	highly alloyed
1.2	Cast iron
1.2.1	Cast iron with lamellar graphite / tempered cast iron
1.2.2	Cast iron with nodular graphite / vermicular cast iron
1.2.3	Highly alloyed cast iron
2	Light alloys, cast and wrought alloys
2.1	Aluminium and aluminium alloys
2.1.1	Cast aluminium alloys
2.1.2	Wrought aluminium alloys
2.2	Magnesium and magnesium alloys
2.2.1	Cast magnesium alloys
2.2.2	Wrought magnesium alloys
2.3	Titanium and titanium alloys
3	Heavy metals, cast and wrought alloys
3.1	Copper (e.g. copper amounts in cable harnesses)
3.2	Copper alloys
3.3	Zinc alloys
3.4	Nickel alloys
3.5	Lead
4	Special metals
4.1	Platinum / rhodium
4.2	Other special metals

Number	Description
5	Polymer materials
5.1	Thermoplastics
5.1.a	filled Thermoplastics
5.1.b	unfilled Thermoplastics
5.2	Thermoplastic elastomers
5.3	Elastomers / elastomeric compounds
5.4	Duromer
5.4.1	Polyurethane
5.4.2	Unsaturated polyeste
5.4.3	Others duromers
5.5	Polymeric compounds (e.g. inseparable laminated trim parts)
5.5.1	Plastics (in polymeric compounds)
5.5.2	Textiles (in polymeric compounds)
6	Process polymers
6.1	Lacquers
6.2	Adhesives, sealants
6.3	Underseal
7	Other materials and material compounds (scope of mixture)
7.1	Modified organic natural materials (e.g. leather, wood, cardboard)
7.2	Ceramics / glass
7.3	Other compounds (e.g. friction linings)
8	Electronics / electrics
8.1	Electronics (e.g. pc boards, displays)
8.2	Electrics
9	Fuels and auxiliary means
9.1	Fuels
9.2	Lubricants
9.3	Brake fluid
9.4	Coolant / other glycols
9.5	Refrigerant
9.6	Washing water, battery acids
9.7	Preservative
9.8	Other fuels and auxiliary means