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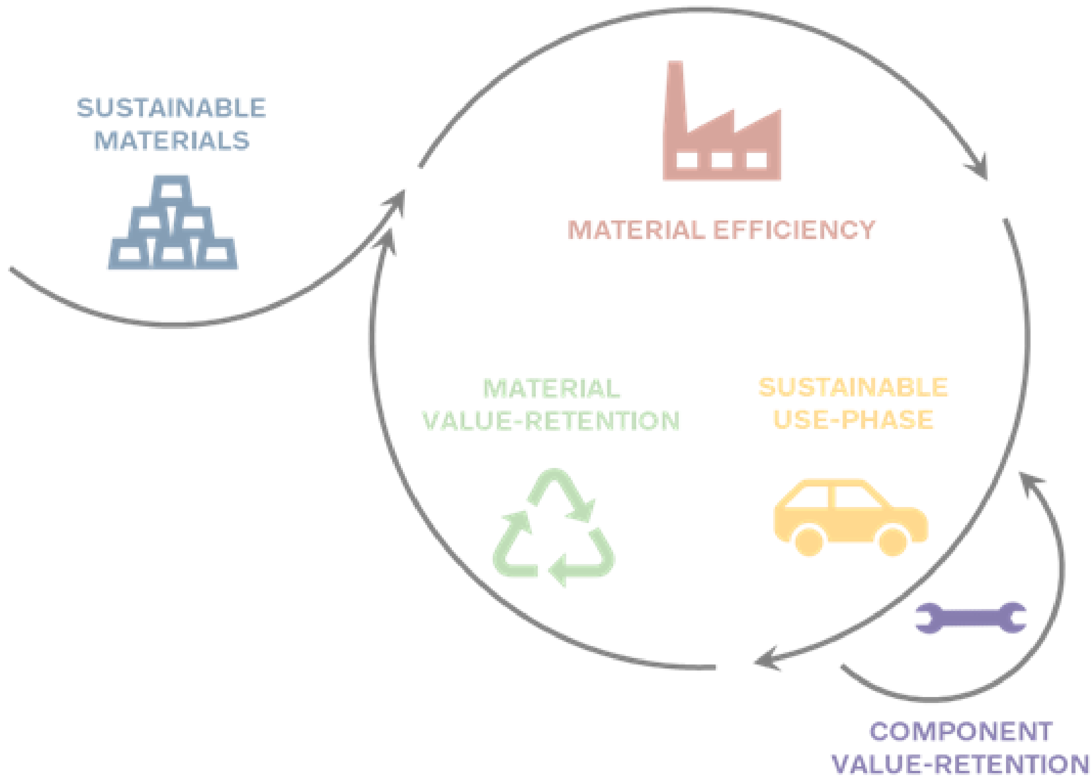

Enabling Circular Life-cycle Thinking and Measuring of Sustainability

From an Industrial Ecologists Perspective

Master’s thesis in Industrial Ecology

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Division of Environmental Systems Analysis

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Cover: Eco design guidelines from a life cycle perspective (Volvo Cars Sustainability Center, n.d.).

Gothenburg, Sweden 2021

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Abstract

Assessing the sustainability of an automotive component can be complex because sustainability aspects need to be balanced against each other. In order to allow the automotive industry to make wise decisions, the industry needs efficient tools which users with little sustainability knowledge can apply to make sustainable decisions in an early concept phase. This thesis researches how such a tool could be constructed and applied to increase the quality of sustainability decisions while expanding circular life-cycle thinking.

This thesis applies the knowledge and conclusions from recent life-cycle assessments of electric machines to build a sustainability calculation tool for the Propulsion department at Volvo Cars. The environmental priority strategy methodology was selected to calculate monetary values for environmental impacts from producing electric machines. One of the results from this thesis is the tool that incorporates the earlier mentioned aspects to create an understanding of circular life-cycle thinking and how efficient end-of-life processes can affect the sustainability of a component. The second result consists of outputs from the tool, which are compared and analysed to determine the tool's accuracy. The complexity of the tool was also checked by having users draw conclusions of tool outputs and comparing those to the researcher's conclusions. The main takeaways from the tool development process are that the tool needed to be very clear and easy to understand. Something evident to the researcher may not be evident to the designers and vice versa.

Keywords: Life-cycle thinking, circular economy, life-cycle assessment, electric machines, electric motors, resource efficiency, sustainability tool, environmental priority strategy, climate change, eco-design, resource life-extending strategies, sustainable development, industrial ecology.

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The thesis was done in cooperation with the Volvo Cars, where I would like to express my gratitude to my supervisor Linnea Petersson, who came up with the thesis idea and supported and mentored me through the entire project. I would also like to say a huge thank you to everyone in the Sustainability Architecture Team for their continuous inputs and feedback. I would further like to thank the team at the propulsion department who helped evolve the tool to something that will be implemented and appreciated at the company.

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Fredrik Byström, Gothenburg, September 2021

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Introduction

1.1 Background

Temperatures are increasing worldwide, and environmental deterioration is happening everywhere. According to IPCC, the global temperature will increase by 1.5°C between 2030 and 2052 compared to pre-industrial levels, with high confidence (Masson-Delmotte et al., 2018). However, the 1.5°C increase will likely be reached earlier. To combat climate change, each part of society must contribute. The transport sector contributed with 8 Gtonnes CO_2 emissions in 2018, where 45 % came from passenger vehicles. The contribution from passenger vehicles stands for 10 % of the total CO_2 emissions (Hannah Ritchie, n.d.). Emissions from the industry sector totalled 17.1 Gtonnes in 2018. Global annual CO_2 emissions add up to approximately 38 Gtonnes and rising year-by-year. To turn the trend around within the automotive industry, action must be taken to mitigate the climate crisis and prevent further environmental deterioration.

The automotive industry needs sustainability tools to take action in the early stages of product development since it is easier and less expensive to make changes early in the R&D process. These decisions need to be scientifically based and accurate. All decisions made must be sustainable from every aspect and not just in the short term of producing an electric vehicle with a low environmental impact. Considerations must be taken regarding the material production and use phase since that is where most of the emissions originate (Egeskog et al., 2020). The global energy sector is transitioning towards less carbon-intensive electricity sources, such as wind and solar power. Combined with a transition towards battery electric vehicles, it will considerably decrease the emissions from the use phase, which means that focus must be placed on selecting the most sustainable materials and manufacturing methods instead, both from an environmental, social, and ethical standpoint. It is necessary to develop knowledge within this area further since it has the largest potential to further improve and decrease emissions.

That is why Volvo Cars have committed to becoming climate neutral by 2040. On this journey, they have also committed to lowering their overall CO_2 emissions by 40 % per car between 2018 and 2025. Their sustainability strategy is based on three different pillars: climate action, circular economy, and ethical and responsible business.

1.2 Purpose & Research Questions

This project aims at exploring possibilities to use life-cycle thinking to increase resource efficiency early in the design process of electric vehicles. The aim is further to suggest what can be done to provide designers with data to make sound sustainable decisions for electric vehicle components.

Research question 1: What should a sustainability tool for vehicle components contain? How can it be adapted for users with limited sustainability knowledge while maintaining adequate accuracy?

Research question 2: How can such a tool be used to increase circular life-cycle thinking without making the decisions too complex?

1.3 Scope & Delimitation's

This thesis project focuses on creating a tool that evaluates sustainability performance from a life cycle perspective. The created tool will be used for electric motors and be possible to adapt to other components. The tool will be built upon the EPS methodology as specified by Volvo Car Corporation (VCC). The tool must be easy to use for a designer with no environmental background and produce a result within minutes to increase the likelihood of the tool being used. The tool must be accurate enough to align with the latest research in the area. However, the tool should only be used to measure the relative difference between solutions and not the absolute values for reporting. Although, the tool can be used to get an approximation at what scale the impacts are. The tool should try to catch more than environmental sustainability.

2
Literature Overview

The literature overview will be presented in the following sections. It will be presented from a life-cycle perspective, starting with an overview of electric vehicles (EV), then diving deeper into the electric motor (EM). These will then be followed by the theory necessary to complete the project regarding resource management, natural capital, and the environmental priority strategy.

2.1 Life-cycle of electric vehicles

Using Life-Cycle Assessment (LCA), it is possible to compare the environmental load from different types of vehicles (Egeskog et al., 2020). A battery electric vehicle (BEV) has a larger manufacturing footprint than an internal combustion engine (ICE) vehicle due to the material required for the electric powertrain (Figure 2.1). This is primarily because of the battery production and partly because more materials are used in a BEV. Further improvement efforts must be aimed at reducing the environmental impacts of materials production and refining, including both EMs and batteries.

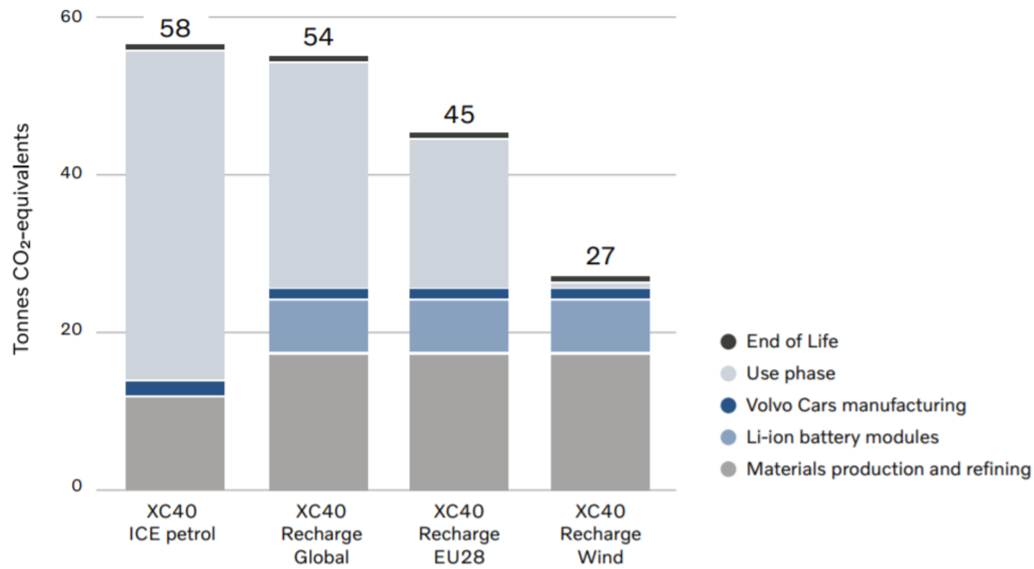

Figure 2.1: Carbon footprint for XC40 ICE and XC40 Recharge with different electricity-mixes used for the XC40 Recharge, (Egeskog et al., 2020).

2.1.1 Electric vehicles

An EV is any vehicle that has some electric propulsion system (e.g. a BEV or a hybrid electric vehicle) (U.S. Department of Energy, n.d.). The vehicle in focus for this report is the BEV powered by only EMs and with no ICE. EVs are increasing the demand for abiotic resources further, and the current supply cannot sustain the current growth (Hernandez et al., 2017). EVs have established themselves on the market in just a few years due to growing air quality concerns and government subsidies. In 2013 only about half a million EVs were sold worldwide, in 2018 it had risen to more than five million, and are expected to reach 250 million vehicles by 2030 (IEA, 2020).

2.1.2 Electric powertrain

An LCA conducted by VCC showed that the difference in the carbon footprint of an ICE vehicle and a BEV lies in the electric powertrain (Egeskog et al., 2020). The high-voltage battery is the main driver of the carbon footprint due to the production processes used. The EM is a key part of the electric powertrain. The power electronics (PE) for the EM can either be incorporated into the EM or kept externally, depending on the vehicle manufacturer (Elwert et al., 2015). The PE consists of the inverter for the EM, DC voltage converter for the onboard electronics, and control electronics for the EM. These will, however, not be analysed further in this project. The typical scheme for an electric powertrain can be seen in Figure 2.2.

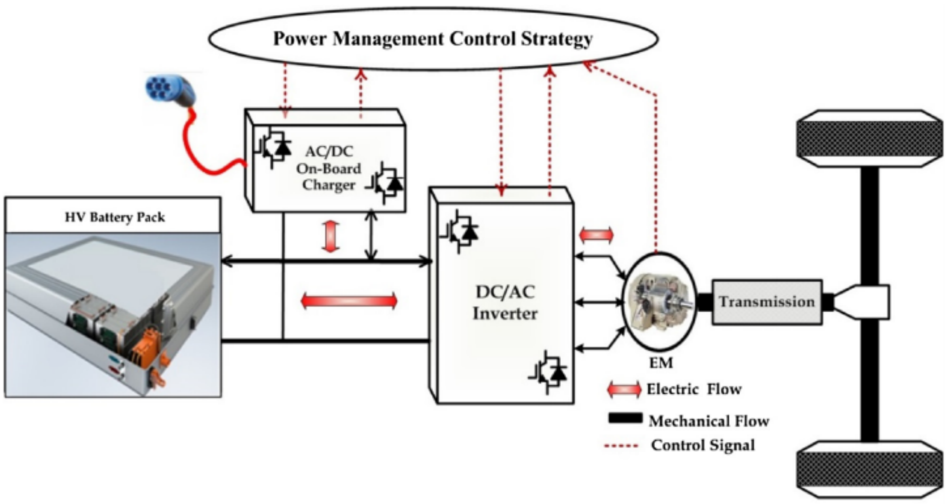

Figure 2.2: Schematic view of an electric powertrain, (Elwert et al., 2015).

2.1.3 Use phase for electric vehicles

EVs have zero tailpipe emissions since the fuel is replaced with electricity. The use phase still has a CO_2 footprint which depends on the type of electricity used. Therefore it is important for electricity generation to have low emissions of greenhouse gases to achieve the lowest total emissions (Figure 2.1). A literature review of conducted LCA's concluded that for EVs to be a climate-neutral option, the electricity generation must also be climate-neutral (Nordelöf et al., 2014). The energy usage during the use phase is determined by driving and simulating the vehicle through a specific driving cycle. The most commonly used test cycle to test the energy usage is the Worldwide harmonized Light vehicles Test Procedures (WLTP). Efficiency is important since this allows for a smaller battery.

2.1.4 End-of-life for electric vehicles

This section will first inform about legislation and provide an overview of the process for a vehicle reaching end-of-life. The problems connected to these will be discussed followed by future challenges.

Due to the end-of-life vehicles (ELV) directive, about eight million tonnes of recycled material is generated in the European Union (EU) each year (EC, n.d.-b). The directive aims to make the recycling and dismantling of vehicles more environmentally friendly. It also aims to ensure that materials are continued to be utilized after end-of-life. Japan, Korea, and China have equivalent legislative ELV recycling systems, while in the US, there is no stand-alone ELV system (Sakai et al., 2014). Where there is ELV legislature, a target recovery rate is commonly set at above 95 % of the weight. Future policy instruments and regulations will be necessary as the ELV directive and manufacturer's responsibility is driving development further to increase the sustainability and circularity of the automotive industry (EEA, 2018).

The separation process diagram for ELV shows an overview of the involved processes in the EU and Japan (Figure 2.3). Hazardous materials are removed, and to some extent easy to remove components as well but most of the vehicle goes to the shredder for fragmentation. Today's fragmentation process leads to the mixing of different materials and makes them even harder to recover. The sheer volume of material is comparatively large and spans across many different categories (Material Economics, 2018).

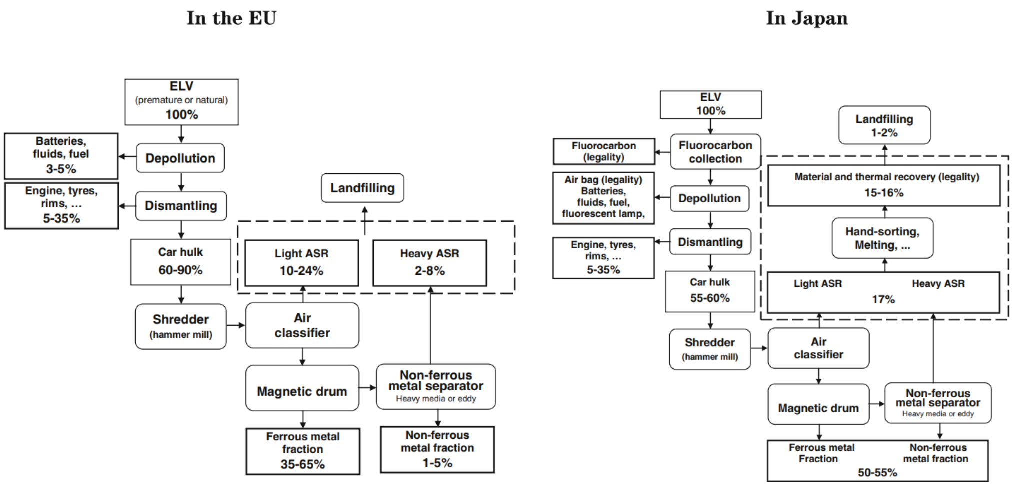

Figure 2.3: Diagram of the processing of an ELV. To the left EU, and right Japan, Sakai et al., 2014.

Problems connected to legislation are that mass-based recycling quotas are not enough as a legislative instrument as they do not give the correct incentives (Sakai et al., 2014). There is a lack of technology and information about ELV management in countries that primarily import used cars, or the system itself is undeveloped due to a lack of legislation. Reaching a global consensus for ELV management systems would be beneficial since the vehicle market is international.

To a greater extent, the recycling process needs to have improved resource productivity by creating more circular material flows. Within the automotive industry there are significant losses of material quality and quantity (Material Economics, 2018). A large portion of plastics is usually combusted for energy recovery or placed in landfills. Steel is downgraded in the recycling process due to the contamination of copper. Only 7-8 % of recycled steel can be used in high-end applications like vehicles once again. High-grade aluminium is commonly mixed with low-grade cast aluminium and can not be used in many other products. Old vehicle collection is not working since it can be a hassle for the consumer to get the vehicle to the proper end-of-life handler (EEA, 2018).

Future challenges are to achieve a higher recovery rate of materials, where environmentally friendly design at all product stages is necessary and to continuously develop recycling systems (Sakai et al., 2014). It is also an opportunity to change legislation at the same time to include targets on material quality after recycling to make a higher recovery rate a possibility (Material Economics, 2018, EEA, 2018). This will be especially important now that society needs to become climate neutral and ensure that resources will be available for future generations. Some vehicle manufacturers have made considerable efforts to incorporate recycled materials in their vehicles. This does not always have the wanted effect if materials are taken out of working circular flows, e.g., using aluminium cans to cast components. However, incorporating design for disassembly in the design process and increasing recycled material content will make them increase the benefit of each other (EEA, 2018). Future ELV legislation is proposing to enforce the use of recycled material in vehicles to improve the recycling processes.

ELV is expected to increase worldwide due to increased vehicle ownership, and the importance of energy effective and efficient ELV system must be promoted (Sakai et al., 2014). In regions with a growing vehicle market, there is an urgent need to establish ELV systems. Techniques to extract valuable materials from ELV require development due to environmental and social issues, especially for EV components.

2.1.5 Life-extending strategies

A circular flow allows for the extended usage of materials and can be done by applying resource life-extending strategies, e.g., reuse, repair, and remanufacture. The goal is to reduce the raw material inputs and waste outputs of the selected system (Figure 2.4). The components should get back to the use phase as efficiently as possible, where reuse & repair is preferred, followed by repair & refurbish, then repurpose & remanufacture, and finally recycle (Ellen MacArthur Foundation, 2017).

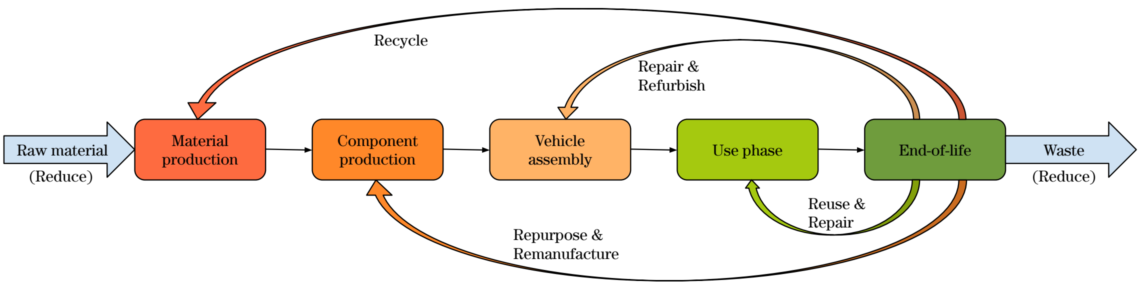

Figure 2.4: Circular life-cycle thinking applied to components in the automotive industry, from material production to end-of-life.

Disassembly for reuse and remanufacturing of vehicles is usually not feasible in Europe with current ELV systems due to labour costs and insufficient support from the manufacturers (Elwert et al., 2015). The automotive industry must incorporate the larger part of the value chain into its processes to allow for a circular economy and a sustainable society.

Renault is a frontrunner within the circular economy field in the automotive industry (Capgemini, n.d.). In the following sections, Renault will be used as an example to shed light on circular possibilities for vehicles by looking at how they started working with circular economy, today's situation, and how their future vision looks.

Renault were early explorers of a circular economy and began to use recycled plastics in 1995 (Groupe Renault, n.d.-a). Since 2000 they have included circular economy in their activities and expanded circular material flows with the goal of turning waste into resources. Sourcing recycled materials create a demand for recycled material, which helps establish a price reflecting the demand. This makes it worthwhile for recyclers to make sure these materials are collected and sorted.

Today, interior fabrics are made from 100 % recycled materials using only mechanical treatment and no chemical or thermal transformation (Renault Group, n.d.). Renault has an entire factory dedicated to recycling old seatbelts, bottles, and various plastics to turn into yarn and fabric, resulting in a 60 % decrease in carbon footprint. Other parts such as mechanical parts are recovered from vehicles reaching end-of-life and are remanufactured and used in new vehicles, or used as spare parts. The recovery is made at INDRA factories which in 2016 recovered 355 000 ELV, 35 % of the total market share in France (EFWMES, n.d.). They overcame bottlenecks by having 350 dismantler stations and recycling and reselling 95.4 % of the vehicle's weight. Renault have achieved this beneficial position by taking control over end-of-life, and having an exchange with organisations such as the Ellen MacArthur Foundation (Groupe Renault, n.d.-a).

Renault is planning to open their Re-Factory in Flins, France. This will be the first circular economy site in Europe dedicated to mobility (Groupe Renault, n.d.-b). The Re-Factory will start implementation in 2021 and finish in 2024, replacing some of the production of new vehicles. It will also host an incubator for start-ups, academic partners and other professionals to accelerate research and know-how within circular economy. The gradual implementation of the Re-Factory will result in four divisions; Re-Trofit, Re-Energy, Re-Start, and Re-Cycle (Figure 2.5). This structure will, according to Renault: "make it possible to support the entire life of the vehicle by acting on the main components of the circular economy (supply, eco-design, economy of functionality, maintenance, reuse, remanufacturing and recycling)" (Groupe Renault, n.d.-b).

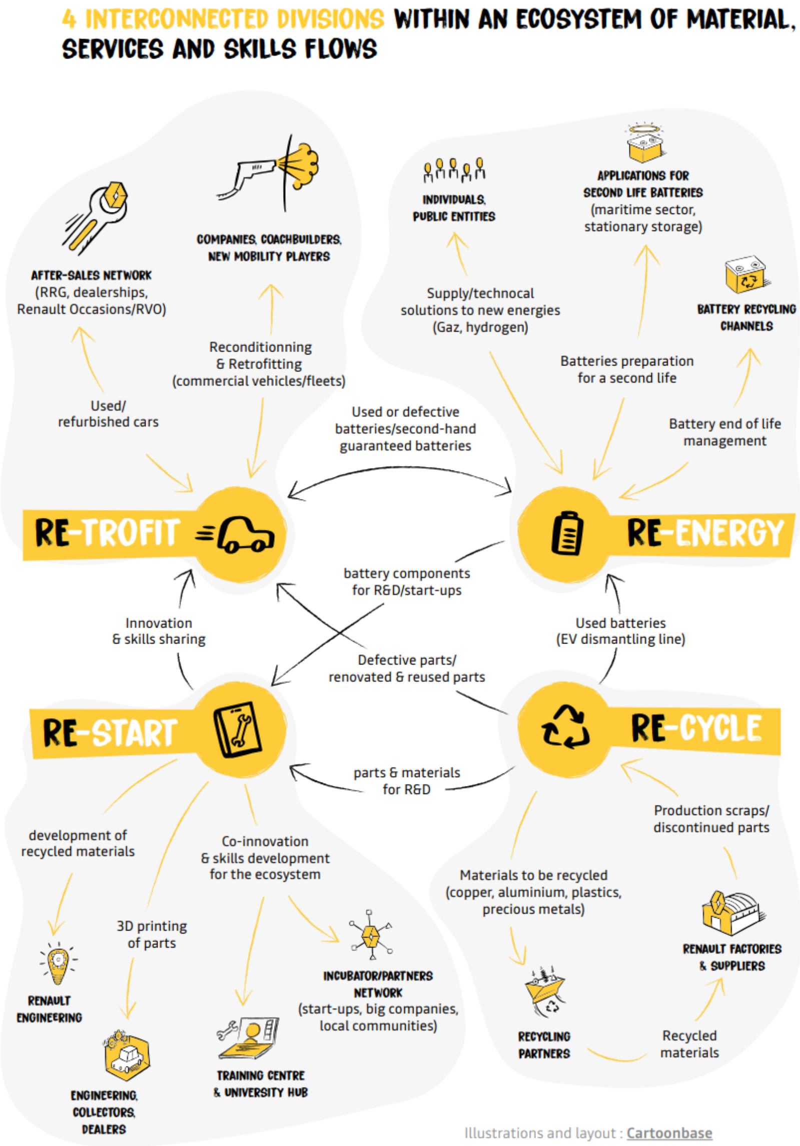

Figure 2.5: Renault's Re-Factory division structure with their respective tasks, (Groupe Renault, n.d.-b).

2.2 Introduction to electric motors

The most important parts of the life-cycle for EMs' from a sustainability perspective are the material extraction and refining, the use phase, and the end-of-life. Manufacturing and transportation contributes to the environmental performance of the motor, but on a minor level.

2.2.1 Electric motors

The primary EM used in the automotive industry is the permanent magnet synchronous motor (PMSM) (Tillman et al., 2020). The most common magnet used for this type of motor is the neodymium-ferrite-boron (NdFeB) type. However, other EMs are also used for vehicles, such as induction motors and variable reluctance motors. The motors follow different design principles and therefore differ in size, efficiency, and weight. However, they do, to a large extent, contain the same materials, except for the addition of magnets in the PMSM. Some features of these three motor types are then combined and thereby creating many variants of EMs. The use of permanent magnets allows the EM to be more energy-dense and energy-efficient while allowing for higher starting torque, thereby saving weight and limiting the use of other materials. According to recent studies, the best EM type from an environmental perspective would be a permanent magnet assisted synchronous reluctance motor (PMaSynRM) (Nordelöf et al., 2019). This EM is an example of how manufacturers have tried to pick out the best traits of each different EM type and combine them into one (Figure 2.6).

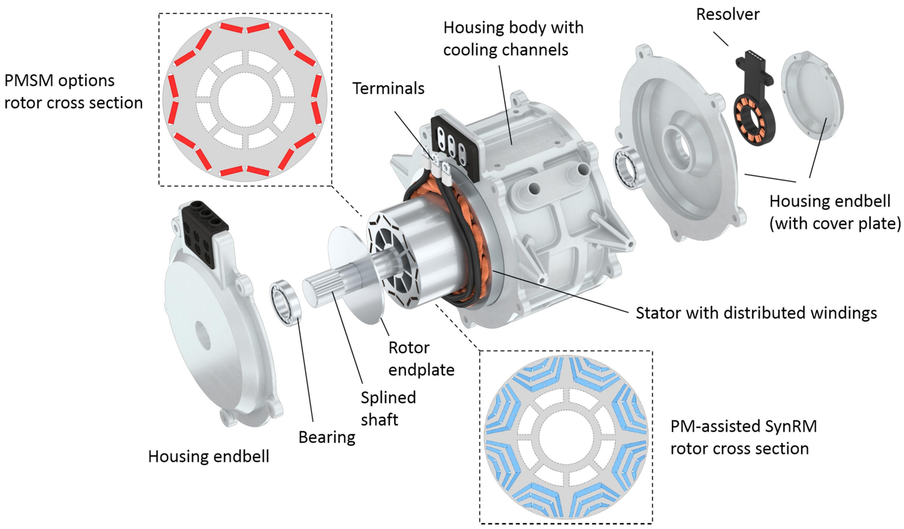

Figure 2.6: Exploded view of the principal design of an electric propulsion motor, with the rotor laminate layouts of a PMSM and PMaSynRM, (Nordelöf et al., 2019).

The raw material composition of the average EM is comprised of copper windings, steel, electrical steel, aluminium, and different plastics (Nordelöf et al., 2019). Electrical steel consists of iron, silicon, and small amounts of aluminium and manganese. All electrical steel in the EM is in the rotor core laminates and the stator core holding the copper windings, most of the aluminium is in the motor housing and endbells, and steel is found in the centre shaft and bearings (Hernandez et al., 2017).

The magnets commonly consist of rare earth elements (REE), where the most common are; neodymium (Nd), dysprosium (Dy), praseodymium (Pr), samarium (Sm) and terbium (Tb) (Elwert et al., 2016, Schulze and Buchert, 2016, Binnemans et al., 2013). Some magnet types also consist of cobalt or strontium. In NdFeB-magnets, ferrite (Fe), i.e., iron, is the primary magnet material followed by Nd; Nd is used due to its magnetic properties; Nd is interchangeable with Pr (Tillman et al., 2020). Dy increases the efficiency of the EM by stopping the Nd from losing its magnetic properties due to increased temperature. Tb is interchangeable with Dy but is more expensive. The magnets can also be manufactured from Sm and cobalt. The benefit of these magnets is higher temperature resistance than Nd magnets, but they have worse magnetic properties and are more expensive. REEs are also used in small amounts in certain ferrite magnets in EMs.

2.2.2 Raw material extraction and refining

The extraction and refining of raw materials contribute to a significant part of the emissions during an EMs life-cycle. That is because it requires plenty of energy to extract and refine virgin raw materials from the earth's crust. Raw material extraction can also lead to social issues for local communities. The materials can be extracted from many different places around the world.

The largest part of the CO_2 footprint for manufacturing EMs comes from the production of aluminium. The CO_2 emissions depend on the electricity used for the smelting process of primary aluminium (Tillman et al., 2020). Other types of environmental emissions are highest for copper mining, where heavy metals may leak into nearby waterways. Steel is the most significant material category in EMs by weight. Steel has a lower environmental footprint than aluminium and copper, but it has an impact due to the amount used. The CO_2 emissions from steel are generated in the reduction process of iron ore.

2.2.3 Extraction and refining of rare earth elements

REE consist of 17 metallic elements belonging to the lanthanide elements, including scandium and yttrium. These metals are abundant in the earth's crust in low concentrations (Petersson, 2019). The REEs can be found as co-products in sulphide ore minerals together with more abundant primary metals such as copper or silver (Tillman et al., 2020). However, it is not economically viable to extract only the wanted REEs. This creates a risk for balancing problems connected to supply and demand (Binnemans et al., 2013). China has 23 % of the world's total reserves of REEs and is the largest extractor of REE's in the world with over 90 % of the total global mass of REEs in 2011 (Wang et al., 2017, Petersson, 2019). Other large mines are found in Australia and the US, where the latter is the most sustainable (Wulf et al., 2017).

An environmental issue with REE ore mining is that it results in radioactive waste (thorium and uranium), the level depends on which ore grade is being mined (Elwert et al., 2016). Furthermore, REE ore mining contributes to local toxicity emissions of heavy metals to the ground and nearby waterways and less significant emissions from fossil fuels during mining in China. The major contributors to greenhouse gas emissions are hydrochloric acid (38 %), water steam (32 %) and electricity (12 %) (Haque et al., 2014). There are efforts in China to make the production more environmentally friendly (Wang et al., 2017). It could be possible to extract REE from secondary sources such as low-grade industrial residues to decrease the environmental impact (Jowitt et al., 2018). In a study at the Kiruna iron ore mine, the mine tailings were studied, and extracting the REEs from the acid mine drainage could be advantageous.

Social issues are prominent in the REE mining industry. It is currently hard to guarantee an REE has been extracted in a socially responsible way due to low amounts of data and lack of transparency (Wulf et al., 2017). The materials pass through either China or other countries, where conditions for workers in and around the mines and handling the materials are inadequate. Some of the social issues of REE mining in China are, e.g., forced labour, excessive working time, no labour laws, and corruption. There have been several illegal REE mines in China, but it is being clamped down by the government. One argument for the need of developing REE extraction, although it has its dark sides, would be to support new green technologies such as wind power, solar, and batteries (Ali, 2014).

2.2.4 Material criticality

Scarcity and criticality of materials are significant challenges for EMs. REE's are classified as geologically scarce, meaning that REEs are found in low concentrations in the earth's crust (Tillman et al., 2020). Criticality means that REEs are exposed to supply chain risks and geopolitical circumstances such as trade restrictions due to their economic importance. Many REEs are on the critical material lists in the EU, the US, and in the OECD (Tillman et al., 2020, Petersson, 2019). Some REE's, such as Nd, is less scarce compared to others such as Dy and Sm. The criticality matrix (Figure 2.7) rates the REEs importance to clean energy compared to supply risk. In the matrix, although it is scarce, Sm is not critical due to low supply risk and demand (Binnemans et al., 2013). Copper is another critical material (Tillman et al., 2020). It is expected to be depleted by 2150 based on current trends of 3 % annual extraction increases until 2050, where it sustains.

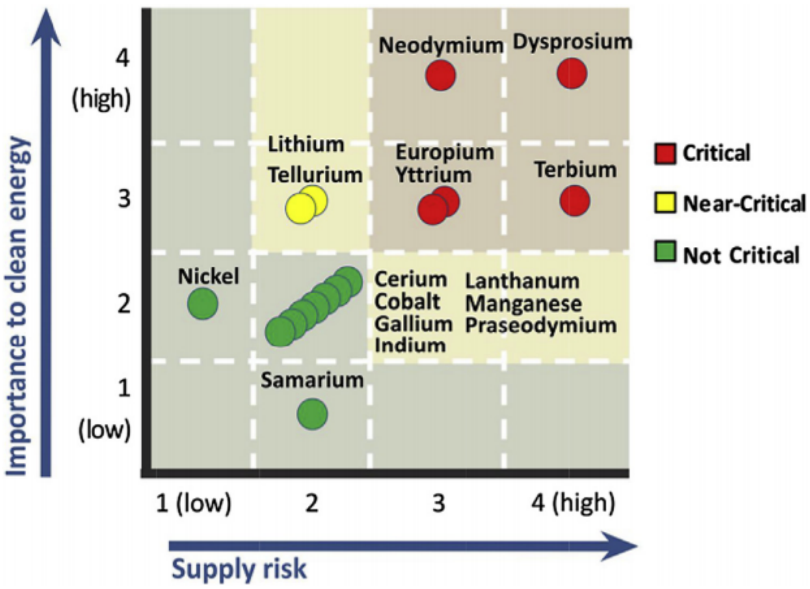

Figure 2.7: Medium-term (2015-2025) criticality matrix, showing critical rare-earth materials, (Binnemans et al., 2013).

To reduce the resource use of EM's, the focus must be to reduce extraction of geologically scarce, and critical materials (Tillman et al., 2020). However, the Dy demand for just EVs in 2030 is expected to be six times the global production due to the substantial demand for new EVs (Sakai et al., 2014). This is important since there is both a long-term supply risk due to resource scarcity, and a short-term supply risk due to costs, criticality, and variations in the supply chain.

The resource use can also be reduced by using circular principles, and the materials used in EM's are optimised. It is possible to remove REEs and replace most of the materials in the EM. Copper can be replaced by aluminium, the one material impossible to replace is steel. However, by removing REEs and copper, the performance would be compromised and potentially result in higher total emissions during its life-cycle.

2.2.5 The use phase of the EM

In the use phase of the EM, the energy usage is important since this will determine the amount of electricity needed to complete a certain distance of driving. Even if the carbon intensity for electricity generation becomes zero, energy usage will still be important since the amount of available electricity will be limited in the future due to increased electrification. However, finding the right balance between efficiency and resource use is necessary to minimise emissions.

To reduce the environmental impacts and resource use, certain things can be done to the design choice of EMs, also impacting the use phase. The copper inside the different EMs can be wound in different ways, where the goal is to have as large share as possible of copper in the active cross-section of the EM to reduce material usage and the size of the overall EM and increase efficiency (Tillman et al., 2020). To accomplish this, a so called hairpin winding or concentrated winding is preferred. Other developments that can reduce the footprint of a motor are developments in magnet technologies, increasing the efficiency of the EM. Current developments are looking into removing the Dy from the magnets due to its high price (Elwert et al., 2015). In the future it will be necessary to find compositions with lower environmental impacts but better magnetic properties. The challenge lies in finding a magnet working in a wider temperature span.

2.2.6 End-of-life of the EM

When an EM is recycled today, it is fragmented together with the rest of the vehicle (Tillman et al., 2020). This leads to unnecessary mixing of materials, which in the end results in higher costs to bring the material back to its original quality. It is also getting harder due to the increased variety of materials used (Sakai et al., 2014). Hence, materials of small quantities such as REEs will get mixed in with the more common materials such as cast iron, steel, aluminium, and copper.

Dismantling vehicles as much as possible before fragmentation reduces the recycling costs and results in higher-grade material flows. This provides an opportunity to provide efficient end-of-life for the EM. Although no REE's can currently be extracted from the ELV established processes due to mixing in the shredding process, recovery of copper and steel is high (Elwert et al., 2015).

REEs are only recycled in China, where there are sufficient quantities to recycle due to large volumes of production waste thanks to Chinas 90 % market share in production (Elwert et al., 2015). Soon, in 10 to 15 years, it will most likely be essential to recycle REEs outside of China to secure the supply as the automotive sector undergoes a significant change to electric powertrains with a drastic increase in demand for these metals (Tillman et al., 2020).

There are ways to recycle the magnets, trialed in the MORE research project, however, they are not commercialised:

1. Manufacturing high-quality magnets by re-melting the existing alloy followed by pulverisation and mixing with magnet powder from primary raw material.
2. Manufacturing lower quality magnets by re-melting the existing alloy followed by pulverisation and a more straightforward binding process.
3. Manufacturing raw material that can be used in high-quality magnets, primarily containing REEs such as Nd and Dy.

There are difficulties with these processes. In the MORE research project it was concluded that methods 1 and 2 led to too high material and functionality losses to be reasonable to use (Elwert et al., 2016). Method 3 was the most readily applicable in the short term, even though it had high economic and environmental costs. When recycling these Nd magnets from scraped EMs, a further challenge is to get them out of the EM. The fact that the industry is currently trying to reduce the usage of these materials makes it even less profitable. Other materials favoured from more efficient recycling in EMs are copper and electrical steel due to unnecessary mixing in the fragmentation process, meaning more work must be put into bringing them back to their initial quality.

2.2.7 Keeping materials in a circular flow

There are some options to increase the circularity of EMs. It is, e.g. possible to reuse complete EM's or separate components, replace components, or implement semi-automated dismantling to improve material qualities both before and after recycling (Tillman et al., 2020). However, to do this, the EM must first be dismantled from the vehicle properly.

Occasions in which the entire EM could be reused is when a vehicle has been in an accident, but no damage has occurred to the EM. It could also be when an EM is sent to troubleshooting or remanufacturing due to malfunctioning, but it proves not to be faulty. A prerequisite for reusing, though, is that the EM is easy to dismount from the vehicle.

When an EM breaks down due to wear, it is most commonly a ball bearing or motor-shaft failure (Tillman et al., 2020). However, these components can easily be replaced with new components and thereby prolong the lifetime of the components important from a sustainability perspective, e.g., the copper winding or the electrical steel rotor housing the REE magnets. The most common cause of failure after those is the isolating material in the copper winding, leading to a short circuit in the stator rendering the EM immobilised. The opportunity in that case, is to reuse the rotor core in another EM, and recycle the stator. By doing this, the loss of high-quality electrical steel and REE's can be prevented (Elwert et al., 2015). This example shows how a material that does not contribute to the resource use in a meaningful way can impact the lifespan of other materials that do contribute.

Using a semi-automated method with hydraulics to dismantle the stator core allows the copper, electrical steel, and aluminium to be completely separated from each other, preventing them from mixing in the fragmentation (Tillman et al., 2020). Research projects have proven that it is already profitable today within the EU to separate the stator and rotor core when recycling EM's before fragmentation (Elwert et al., 2015). The profitability is primarily due to the high copper content of the stator. Semi-automated dismantling of EMs allows extraction of the magnets, which is the only way to allow the REE's to be recycled. A hydraulic press tool will be necessary to dismantle the end plates from the core to allow the magnets to get extracted when mounted internally.

2.3 Resource management

Resource management of natural resources is essential from a sustainability perspective since they are limited. Meaning resources must be shared evenly and efficiently. Corporate responsibility is a vital part of the solution.

2.3.1 Global material productivity

Currently, the relation between economic development in the world is coupled with the ecological and social impacts (IRP, 2019). Economic growth is heavily dependent on the extraction of primary resources, the linear economy. This is because companies are still earning a majority of their income from selling goods. The global use of resources has tripled since 1970, and it was at 92 Gtonnes in 2017. This is coupled with the increase in wealth around the world and our current lifestyle. Our use of natural resources is risking to de-stabilise the climate system. Although resource use can be connected to economic stability, it also plays a massive role in many conflicts and migrations (IRP, 2019). Corporations are aware of the difficult situation and have tried targeted efforts at specific problems. However, a holistic view is needed to guarantee the success of these initiatives. E.g., improving the work conditions for people in Congo working in cobalt mines has given results. In contrast, using biofuels to reduce CO_2 in many cases negatively impacts biodiversity by giving rise to large monocultures.

Global material productivity has decreased since 2000. It has increased in developing economies, but since the production has moved away from the production efficient economies to developing economies, it has become worse (IRP, 2019). Resources are also unequally consumed, high-income countries consume annually 27 tonnes of materials per capita, and low-income countries 2 tonnes per capita. High-income countries usually import lots of end products (e.g., clothes, electronics) manufactured in middle-income countries. The resource dependency of high-income countries has increased by 1.6 % annually. On average, in 2017, one person in a high-income country relied on 9.8 tonnes of primary materials from other parts of the world.

2.3.2 Future resource management

The International Resource Panel (IRP) created two different future scenarios for resource use (IRP, 2019). One scenario is based on historical trends, which would allow global resource use to increase to 190 Gtonnes (92 in 2017) per year by 2060. The other scenario is towards sustainability, and it includes resource management and efficiency initiatives to mitigate environmental dangers, improve well-being, and provide economic growth. In this scenario, economic benefits would be visible in 2030 and increase further until 2060. The annual material extraction would be 25 % lower than in the historical scenario, coming in at 143 Gtonnes in 2060, and the productivity would increase by 27 % from 2015 to 2060. A more even resource use between high- and low-income economies could also be observed, with high-income at 13.6 tonnes per capita and low-income at 8.2 tonnes per capita. In 2060, there has also been a decoupling between environmental impacts and economic growth, thanks to resource efficiency policies.

The metals category differed the most between the two scenarios at 48 % less in the towards sustainability scenario than the historical trends scenario. The critical component enabling this to occur was that the extracted metals could be used indefinitely, but recycling, reuse, and remanufacturing must be done correctly. However, this means a sustained extraction of today's levels because of the expected growth in low-income economies, where steel will be important for infrastructure projects.

2.3.3 Resource inefficiencies in the value chain

The use of natural resources is inefficient, a large share of the monetary value is lost. In a country such as Sweden, where there are comparably high recycling rates and good handling of materials, the economic losses due to inefficient resource use are substantial (Material Economics, 2018). Each year in Sweden, there is an approximate value loss of 30 billion SEK due to volume-, and price-losses. The volume losses are due to the material being combusted or deposited instead of recycled, and then there are general losses in the entire value chain. Dominating this category is steel at 6.9 billion SEK and plastic at 8.2, totalling 15.1 billion SEK. The price losses are due to contamination, mixing, and uncertain quality of materials. This category is dominated by steel, with a total of 5.1 billion SEK. A significant problem for Swedish steel recycling is the contamination of copper, which is expected to worsen considering the increased production of EVs. Furthermore, 3.1 billion SEK of aluminium falls out of the Swedish value flow each year. The aluminium value chain is different from steel and plastics because it is more globalised, where 40 % of the yearly use is imported, and 30 % of the scrap is exported. The value of aluminium is well retained because the demand for high alloy aluminium is high in the automotive industry, and it stands for 55 % of the usage of recycled aluminium.

2.3.4 Corporate responsibility

To allow continued growth for companies in the future, the environmental and social impacts must be decoupled from the economic growth (IRP, 2019). To make this a possibility, companies must create a vision of how this resource decoupled future can look like for their business. As mentioned previously, it is important to incorporate the entire value chain in this vision (IRP, 2019). Decisions should be based on facts for direct and indirect use of materials. There are frontrunners in each sector and these companies should act as inspiration of what is possible. These have e.g., successfully switched from product based to function based offerings, and applying digital solutions to decouple from material usage. To reach the vision, resource decoupled economic growth, short term resource efficiency improvements must be combined with long term changes to improve the systematic conditions for a decoupled value model. The key considerations according to the IRP are:

1. What can the businesses do to change product design and create more value from resources across the entire life-cycle? E.g., designing products for reuse, repair or remanufacture.
2. How is it possible for businesses to change the materials used to more sustainable options? E.g., other material types, recycled or reused materials, better suited to new business opportunities.
3. How can new digital solutions and applications support the businesses? E.g., increasing transparency and traceability in value chains, or create new markets allowing for circular models to become increasingly profitable.
4. What internal incentives, communications and organisational structures can be created to support a resource-efficient transition? E.g., shareholder bonuses based on sustainability KPIs.

5. How would a business be affected by continuing to exceed the planetary boundaries? E.g., negative brand exposure, stranded assets or difficulty to stay relevant.

To sum up the corporate responsibility, even if no guidelines or policy currently prohibits a particular practice. Not trying to move away from a practice that is not sustainable in the long term can become a cost for the corporation (IRP, 2019). Hence, moving towards the best available solution is in the interest of a competitive corporation. This is, however, seen as a risk due to uncertainties in policy-making.

2.4 Natural capital and Environmental Priority Strategy

This section aims to connect the definition of natural capital to the EPS methodology used in this project.

2.4.1 Definitions of natural capital

Natural capital is everything around us, provided by nature. There are many definitions of natural capital, here are some of them to exemplify:

1. "Natural capital can be defined as the world's stocks of natural assets which include geology, soil, air, water and all living things. It is from this Natural Capital that humans derive a wide range of services, often called ecosystem services, which make human life possible." (WFNC, n.d.)
2. "Natural capital are natural assets in their role of providing natural resource inputs and environmental services for economic production." (OECD, n.d.)
3. "Natural capital is the world's stock of natural resources, which includes geology, soils, air, water and all living organisms. Some natural capital assets provide people with free goods and services, often called ecosystem services." (Wikipedia contributors, 2021)

There are many ways to categorise natural capital. The important part is knowing what is meant with natural capital (UN, 2014). There are geological resources, e.g. minerals and metals, and energy resources such as crude oil and coal. Also, there is ecosystem capital, and this can, e.g. be timber or water resources. Finally, there are the planetary systems such as the greenhouse effect and wind. The natural capital yields benefits for the people and society through geological resources, ecosystems, or planetary systems (Natural Capital Coalition, 2016). Geological resources are categorised as non-renewable and depletable, while the planetary systems are renewable and non-depletable (UN, 2014). The ecosystem capital is both renewable and depletable, it depends on our usage. According to The Economics of Ecosystems and Biodiversity (TEEB), setting a price on natural capital may seem callous (EC, n.d.-a). However, this lack of monetary value can be the root problem for our economically based system's unsustainable use of natural capital.

2.4.2 Environmental Priority Strategy

The EPS system was developed in the 1990s to facilitate environmental priority strategies in the product design or situations when a choice between two or more designs are necessary (Steen and Rydberg, 2020). EPS can be considered a comprehensive measurement of sustainability due to it including many impact categories. EPS builds on the ISO standards associated with LCA (ISO 14040 and ISO 14044) and the standard ISO 14008 for monetary valuation of environmental impacts and aspects.

The starting point of EPS is the Brundtland definition of sustainability, where the focus is the natural capital and the ambition that the next generation inherits a natural capital in an equal or better state than the previous generation inherited it (WCED, 1987, Steen and Rydberg, 2020). Furthermore, a decrease in the natural capital creates a debt equal to the cost of restoring that natural capital. The debt can also be equal to a compensation accepted by the individual subject to the consequences of losing the natural capital. Future generations, however, cannot accept compensation since their valuation of natural capital is unknown. Therefore, only impacts excerpted on the current generation can be considered. The complete EPS architecture is shown in Figure 2.8. The unit used in EPS is called environmental load unit (ELU), where one ELU is equal to one Euro in cost for society.

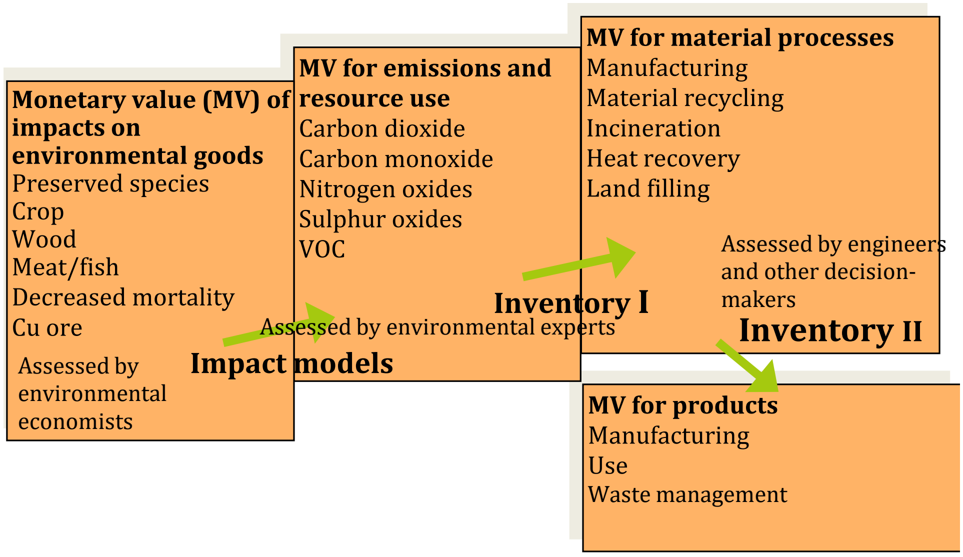

Figure 2.8: EPS architecture, the workflow is starting in the left box, (Steen and Rydberg, 2020).

The components of the EPS architecture illustrated (Figure 2.8) also represent the workflow of EPS. The relevant environmental goods to be used in the assessment are selected from the natural capital. Then, the values for environmental impact indicators on the environmental goods are considered, i.e., the cost of losing 1 unit of a specific natural capital is determined, as described in the previous section. This evaluation is done by environmental economists and follows the standard ISO 14008 (Steen and Rydberg, 2020).

Secondly, the monetary valuation of resource use and emissions are determined using impact models, i.e., the cost for the impacts on the natural capital is determined. These flows are then connected to the different environmental impact indicators, and environmental experts do this second step.

The third step includes determining monetary values for environmental impacts from material processes, that is, what emissions are generated and what resources are used to complete each step of the life-cycle. These processes are, e.g., production, transport, and recycling; environmental experts also complete this step.

Finally, the monetary impact value of the product(s) is calculated. The final step is what the tool developed in this project allows the product developer or decision-maker to do by themselves. The EPS data can be found in databases such as ecoinvent.

2.5 Volvo Car Corporation

VCC is a car-maker with 40,000 employees worldwide (Volvo Car Corporation, n.d.-a). The headquarter of the company is in Gothenburg, Sweden. In 2020, VCC managed to sell 661,713 cars in total in about 100 countries. VCC targets the premium-segment of cars and the largest markets are China with 25 per cent of the total sales volume, followed by the US (17 %), Sweden (8 %), Germany (7 %), and the UK (7 %).

2.5.1 Sustainability strategy

VCC aims to be a climate-neutral and circular company by 2040 (Volvo Car Corporation, n.d.-a). VCC has also set an aim to only produce electric vehicles after 2030. However, producing electric vehicles alone will not achieve climate neutrality. The supply chain and broader operations will also have to be included in combination with recycling and reusing materials. VCC's sustainability strategy is focused on three different areas; climate action, circular economy, and ethical and responsible business. VCC is not the only company having high ambitions in these three sustainability areas. There is a race among car companies to become climate neutral. Not achieving the set targets will influence the brand value. A key selling point for VCC on top of safety is sustainability. If the brand were perceived as not being a leader in the area, it would be a high cost for the company.

The strategy for climate action is based on the recognition of the transport sector contributing to climate change through CO_2 emissions and having a responsibility to act upon it (Volvo Car Corporation, n.d.-b). Between 2018 and 2025, the commitment is to reduce the carbon footprint per average car by 40 %. This will be achieved by reducing tailpipe emissions by 50 %, decreasing raw materials and suppliers footprint by 25 %, and the total operation and logistics by 25 %.

Volvo's strategy for circular economy aims to retrieve parts and materials at the end of the vehicles technical lifetime (Volvo Car Corporation, n.d.-b). The cars are designed to minimise waste and are using recycled and bio-based materials. Their circular economy ambitions are to have 25 % recycled and bio-based content by 2025. VCC has started to use Circulytics (Ellen McArthur's circularity measurement) to measure the circularity of the company. The metrics highlight the importance of the material being used and the repairability of the components making up the product. The metrics also compare the company to the industry average, which means that to receive a high score and be a circular business, one needs to be a leader in the industry. This is an excellent driver to improve the products.

Volvo's ethical and responsible business strategy covers a wide area, from how their employees are treated, to supplier collaborations and the environmental and social impacts from raw material sourcing (Volvo Car Corporation, n.d.-b). They strive to be leaders within ethical and responsible businesses in their business segment. One example of how VCC promotes responsible sourcing of minerals and metals is by using blockchain technology to track cobalt used in the batteries throughout the supply chain. Furthermore, business partners are expected to perform activities in order to reduce their environmental impact and ensure their materials are sourced in a socially responsible way and not contributing to human rights abuses.

2.5.2 The early design phase

The production system used at Volvo allows the engineers to work with several technologies in parallel in the early design phase. The design choices are narrowed down and only a few design reaches the architecture phase where the design is set prior to industrialisation of different vehicles. The sustainability must be determined in each phase, going from more or less sketchy design ideas to detailed constructions. The aim is that the tool should be used throughout the different design stages. It is key that the tool works in early R&D phases, since the technology concept is normally decided at this stage. It is therefore important to understand the sustainability impacts from the different concepts being investigated to ensure that sustainability is considered during evaluations.

The second phase is the concept engineering development, this is a phase where some concepts have been created and it is time to start comparing the concepts against one-another. Some input variables will be known and concepts that do not meet the set demands will be sorted away. The third step is the detailed engineering development, where most input data will be known and improvements of components regarding sustainability is possible. Finally is the design verification and system tests phase, where several parts of the system will be tested together to allow for system optimisations.

3
Method

This chapter aims to present the methodology used to answer the research questions. The project started with a wide literature search and review to fully understand the problems in the EM life-cycle. This was followed by discussions of how the sustainability performance would be captured in the tool. Then it was time to start the iterative tool creation process. Once the tool was deemed finished, it was evaluated and tested.

3.1 Data Collection

This section describes how the necessary data was collected in order to conduct the thesis and reach the aim of it. First, a literature search and review was conducted, followed by dialogue with the design team. The data used in the tool was then collected, and finally, the eco-design questionnaire was formulated.

3.1.1 Literature search & review

The literature search focused on retrieving info regarding the problem with EMs from a life cycle perspective. The primary sources for finding these articles were (1) google.com and (2) sciencedirect.com. The used search terms in combination and variations to find the proper literature: Life cycle assessment, electric machines, electric motors, natural resource use, planetary boundaries, resource depletion, material use, hybrid vehicles, electric vehicles, rare earth elements, NdFeB magnets, permanent magnets, recycling, social and environmental impacts, life cycle models, resource outlook, end-of-life vehicle, disassembly strategies, circular economy, circular flows, eco-design, and sustainable development. The search was conducted from January to March. Some literature was also acquired through the supervisor at the company. There was a specific focus for studies and research conducted by Nordelöf et al. at the Chalmers University of Technology, which have focused on LCA studies of different EMs for EVs. When the literature review was finished, a meeting was arranged with Anders Nordelöf to summarize the findings and make sure the proper conclusions had been drawn.

3.1.2 Dialogue with the design team

Metrics were defined to determine the sustainability performance of components from a life-cycle perspective. By using CO_2 eq. it was possible to determine climate change which can easily be related to VCC's CO_2 sustainability targets. Hence, CO_2 eq. was used as they can help to assess the climate action contributions from material production, use phase, and end-of-life. Secondly, a more comprehensive sustainability parameter was wanted that reflected more impact categories than just CO_2. This was important since material extraction and refining is associated with many more environmental and social issues, and in decision-making, this should be considered. As a result, EPS was selected as a methodology to complement CO_2. The EPS methodology enables the monetisation of natural capital, which can have social and ethical impacts such as loss of expected lifetime and diseases due to emissions. Finally, since the literature pinpointed copper as the most prominent material problem and still is commonly used, a measurement to capture those effects were necessary. Human toxicity seemed fitting as there are large quantities of toxic waste being generated when extracting copper. Using the three selected impact categories seemed to give a broad scope of the sustainability data provided in the tool.

3.1.3 Data used for modeling

The data used in the modelling was attained through the Chalmers supervisor together with IVL. Sphera, and ecoinvent 3.6 and 3.7.1 was used in order to attain the values and data-sets. All values were confirmed and aligned with data used internally by VCC, to make sure similar data had been used when setting sustainability goals. The most important data to align with the internal data was the electricity mixes. The data used for all the materials were current data, hence, the data must be updated periodically for the accuracy to remain adequate.

3.1.4 Developing eco-design questionnaire

The questionnaire contains questions based on the design for sustainability guidelines (Marcel Crul and Jan Carel Diehl, n.d.). These guidelines were modified and split up into categories according to VCC's internal eco-design guidelines. The questions were adapted to designers, and some questions more specific to the EM was created. The results of these steps were communicated with sustainability experts within VCC to make sure they were of relevance. During meetings with the design team, the questions were discussed to make sure they were understandable and could fulfil their purpose of increasing circular life-cycle thinking.

3.2 Tool Development

This section describes how the tool was created using the data collected in the previous section. It also describes the calculations completed in the tool and how it was evaluated together with the users. Finally, it describes how the accuracy of the tool was tested and evaluated.

3.2.1 Development process

Microsoft Excel was used to create the tool, and it was created using an iterative process. Excel enables fast development and easy updating. It also provides an interface that designers are used to. The findings from the literature review were used to find parameters reflecting the impacts and problems associated with producing EMs. Each presented version of the tool will be described in this chapter in version 0, version 1, version 2, and version 3. The final version is handled in the results chapter.

For version 0, the most important findings in the literature review were presented together with a proposition of input and output parameters to a selected group of three people, a core team at the propulsion department to get their feedback. The proposed input and output parameters can be seen in Table 3.1.

Table 3.1: Proposed inputs and outputs of the tool.

Input parameters	**Output parameters**
Material	ELU
Material weight	CO_2 equivalents
Energy efficiency	Range
Expected lifetime	GWP100
CO_2 intensity of electricity	Human toxicity
	Water usage
	Regional CO_2 differences
	Ethics
	Circularity (questionnaire)

Specific questions were formulated to get proper feedback on the ideas for the tool. These questions were also to make sure the correct scope of the tool had been captured.

1. What will the tool be used for?
2. What do you want out from the tool?
3. Do you have a material list available (with the materials you can use when designing an EM)?
4. Should you be able to update the tool?
5. To handle end-of-life issues, how about having a questionnaire in the tool to ensure sustainable thinking?

When creating version 1, the feedback from the version 0 presentation was taken into account when starting to develop the sustainability tool. The tool took shape in the form of several tabs, each with a specific task. When opening the tool, the first tab contained an information box that explained the purpose of the tool and what each tab would contain. The second tab contained input parameters and results for the first component, and the third tab contained input parameters for the second component. The selected input and output parameters in Inputs & Results 1 and 2 tabs can be seen in Table 3.2.

Table 3.2: Selected input and output parameters in Inputs & Results 1 and 2 tabs in tool version 1.

Input parameters	**Output parameters**
Energy usage	Climate change
Expected lifetime	Human toxicity
Electricity mix	EPS
Component name	
Main materials weight	
Magnet materials weight	
Recycling % materials	
Re-use % materials	

These tabs were then followed by the comparison tab, where output parameters are displayed from each part of the life cycle and some figures to create a ground for decision-making. The questionnaire tab had also been formed but only as a rough draft with some questions, then there was calculation- and data tabs.

A meeting was held where version 1 was demonstrated, and feedback was collected. The feedback was then incorporated into version 2 through discussions with relevant people and the supervisor at VCC. The first information tab was left unchanged, and in the inputs & results tabs, the end-of-life inputs were removed. The input och output parameters contained in this version can be seen in Table 3.3.

Table 3.3: Selected input and output parameters in Inputs & Results 1 and 2 tabs in tool version 2.

Input parameters	**Output parameters**
Energy usage	Climate change
Expected lifetime	Human toxicity
Electricity mix	EPS
Component name	
Main materials weight	
Magnet materials weight	

The comparison tab remained essentially unchanged apart from introducing a decision-making box, which determines what component seems to be the most advantageous from a sustainability perspective. This was introduced to support the designers in the decision-making process if different components would come out on top in the impact categories. Since EPS is an end-point impact category, and to avoid greenwashing, the decision is primarily made on the EPS values and adding in a minor weighing of the climate change mid-point impact category. The questionnaire was changed; it now contained questions categorised accordingly to the eco-design guidelines categories; sustainable materials, material efficiency, sustainable use phase, component value-retention, and material value-retention. The removed inputs Recycling % materials and Reuse % materials, and their associated tables were moved to the questionnaire tab since they are not necessary inputs to get a comparable result. Furthermore, they were only used to calculate the potential of end-of-life. It also seemed fitting as they could now be filled in while going through the questionnaire. To increase the understanding regarding end-of-life, a diagram to visualise the current recycling situation was introduced; it also suggested potential parts to reuse.

Another meeting was held to demonstrate the tool's capabilities and get further feedback, and the same methodology was applied to the feedback. In version 3, the information tab had now gained an instruction box on using the tool, complemented by a box with assumptions made in the tool's calculations. The Input & Results tabs remained essentially unchanged, apart from introducing a table with a standard material composition of the most common magnet types. This table would allow the designers to pick the correct magnet materials by only knowing the magnet type. The comparison tab was changed, the end-of-life results were removed entirely from the comparison and the decision-maker box. The input table for Recycling % materials and Re-use % materials were moved from the questionnaire to a new end-of-life tab after the questionnaire, together with everything regarding end-of-life. This restructuring would reinforce the fact that only the end-of-life potential is calculated, not the actual end-of-life impact, as there is no system set up to guarantee what end-of-life will occur. A new figure to better explain where circular resource life-extending strategies could end up in the value chain was introduced (Figure 4.3).

3.2.2 Calculations and assumptions

The calculations in the tool are done using the equations and assumptions in this chapter. Impacts for the production phase are calculated using equation 3.1, with the following assumptions: only the material extraction and refinement is considered, no recycled material is used, there are no regional changes on material sourcing e.g. aluminium data is a european average, and the impact factors are based on current data. Where the impact factors in all equations are: Climate change=kg CO_2 eq./kg, Cost for society=ELU/kg, Human toxicity=kg DCB eq./kg. Impact factors were attained from ecoinvent and Spera.

$$\text{Material weight} \cdot \text{Impact factor} = \text{Impact}_p \tag{3.1}$$

Impacts for the use phase are calculated using equation 3.2, following the same methodology as Nordelöf et al., 2019 used. This methodology allows the impacts of the use phase belonging to the specific component being investigated to be allocated to it instead of the impacts for the entire vehicle. Energy usage is measured in Wh/km, and Carbon intensity in kg CO_2 eq./kWh, ELU/kWh, and kg DCB eq./kWh. Impact factors were attained from ecoinvent and Sphera.

$$\text{Energy usage} \cdot \text{Carbon intensity} \cdot \text{Distance} = \text{Impact}_u \tag{3.2}$$

Impacts for end-of-life when recycling are calculated using equation 3.3. By recycling a material, a negative credit is accounted for the component because the material can then be used in new components. Standard recycling rates for the most common materials were found in the literature. Impact factors were attained from ecoinvent 3.7.

$$\text{Material weight} \cdot \text{Impact factor} \cdot \text{Recycling rate} = \text{Impact}_r \tag{3.3}$$

Impacts for end-of-life where the circular resource life-extending strategies; reuse, repair, refurbish, and remanufacture was applied are calculated using equation 3.4. This can be applied to specific parts, hence not only reuse. Impact factors were attained from ecoinvent 3.7

$$\text{Reused material weight} \cdot \text{(-Impact factor)} = \text{-Impact}_p \tag{3.4}$$

3.2.3 Evaluating the tool with users

A final meeting was held with a larger number of engineers from propulsion to examine if the engineers found the tool easy to use and understood the key concepts of the tool. The tool was also handed over to a designer with material inputs entered to compare the user's conclusions to the same research used to test the tool's accuracy. First, the comparison tab was reviewed twice, one time with the global electricity mix selected, then with the wind electricity mix selected. The designer was asked to give their thoughts about the climate change impact and the cost for society impact. Secondly, the person was also asked to compare the performance of the components with reuse being applied to end-of-life to make sure the tool reflected the importance of applying circular resource life-extending strategies. Suppose the designers could come to the same conclusions as to the literature, by using fewer inputs and within the period of a short meeting. In that case, the tool can be viewed as adequately accurate without being too complex.

3.2.4 Testing the accuracy of the tool

The accuracy of the tool was benchmarked against the most up-to-date research within the EM area by Nordelöf et al., 2019. The input materials were attained from the supplementary report of Nordelöf et al., 2019 together with the use phase's energy usage values. No end-of-life was calculated in this comparison. The PMSM with Nd(Dy)FeB magnets were selected to be compared with the PMaSynRM with Sr-Ferrite magnets. There were two different electricity mixes, one carbon-intensive global mix and another low carbon-intensive wind-based mix. The results were compiled in a figure and compared to the results of the LCA. The comparison was made by comparing the relative differences between the impacts of the life-cycle phases.

3.3 Analysis strategy

This section describes how the analysis will be conducted in order to answer the research questions.

3.3.1 Research question 1

Results from the impact categories climate change and cost for society from the tool will be compared in order to highlight the importance of basing decisions on parameters that reflect sustainability in a more true way. The same results will then be compared again, but now including end-of-life where the component is reused to highlight the significance of being able to guarantee efficient end-of-life handling. The simplifications done in the tool will be discussed to show how the tool was adapted to user with limited sustainability knowledge. Finally, the climate change results from the first comparison will be compared to climate change results from the literature, in order to establish the accuracy of the tool.

3.3.2 Research question 2

Firstly, a comparison between decision making without the tool and with the tool will be conducted. This will be done by looking at the contributions of the tool, and the results from the evaluation with the user. Secondly, the complexity of decisions previously vs. now will be compared by studying optimisation metrics, to show how the tool makes it possible to consider sustainability. Finally, an analysis of the contributions from the tool in future decisions will be carried out, and how the tool can contribute in realising more sustainable products.

4

Results

This chapter will present the results from using the selected methodology.

4.1 Tool design and content

After going through the tool creation process, a final version of the tool was created. In Figure 4.1, it is possible to see the most important steps of the tool where the user will spend most of their time and how to move about in the tool's iterative process. The iterative cycle will be gone through several times during the early concept phase.

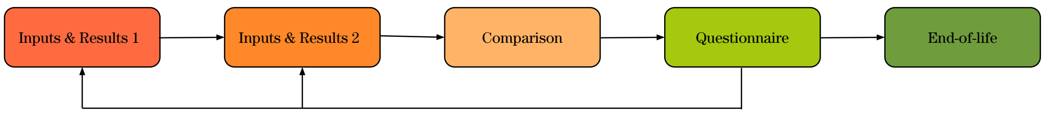

Figure 4.1: The important steps of the final tool visualised, starting from Inputs & Results 1.

4.1.1 The initial steps

Inputs & Results are where all necessary inputs are given, allowing for ease of use. Additionally, a brief overview of the results is presented, enabling the user to see the results updating in real-time. The comparison enables the user to better understand the impacts of each component by looking at the graphs and figures presented together with the output parameters, without end-of-life taken into consideration. The tool will also suggest which component seems to be the best from a sustainability perspective, and this is done by weighing the impact categories against each other. Most importantly, all information necessary to come to a final decision on the best component is available.

4.1.2 Eco-design aspects

To ensure sustainability has been considered when designing the component, the user continues with the questionnaire. In the questionnaire, Figure 4.2 is available to visualise the five essential categories of the life-cycle when designing a more circular and sustainable component. The questionnaire is connected to each category and is formulated to be relevant for designers. Sustainable materials are about selecting materials with low ecological impact, lower scarcity, and using recycled materials. Material efficiency connects back to the production techniques used, the material wasted in the production, and what energy source is used in the factory. The sustainable use phase questions focus on making the components lightweight and efficient, and not emitting harmful materials. Component value-retention concentrates on designing components that are easy to maintain, repair, and make it possible to upgrade them in the future. Finally, material value-retention aims to make the component easy to dismantle and reuse, refurbish, remanufacture, repurpose, and recycle by making sure the components can be easily removed from the vehicle, make it easy to disassemble the parts, and separate the materials. To help answer the questionnaire, the user have all calculations and data available in the tool, everything is visible and transparent.

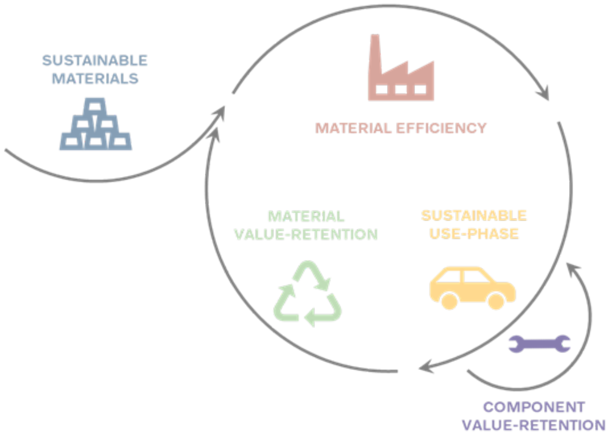

Figure 4.2: Eco design guidelines from a life cycle perspective (Volvo Cars Sustainability Center, n.d.).

4.1.3 Circularity and end-of-life

Figure 4.3 is introduced to show what resource life-extending strategies can be applied to the component according to circular life-cycle thinking. It is possible to see where each strategy ends up in the value-chain, reuse & repair leading back to the use phase, repair and refurbish to the vehicle assembly, repurpose & remanufacture to the component production, and finally recycle back to the material production. These strategies then enable a reduction in the inflow of raw material and outflow of waste from the system. The reduction is the wanted result from applying the strategies by going through the questionnaire. If there are improvements to be implemented after completing the questionnaire, the simulations used to attain the initial input values is re-run and the new values are entered in the inputs and results. However, if the results are satisfactory and several iterations have been completed, end-of-life is next to realise the potential savings of the different impacts.

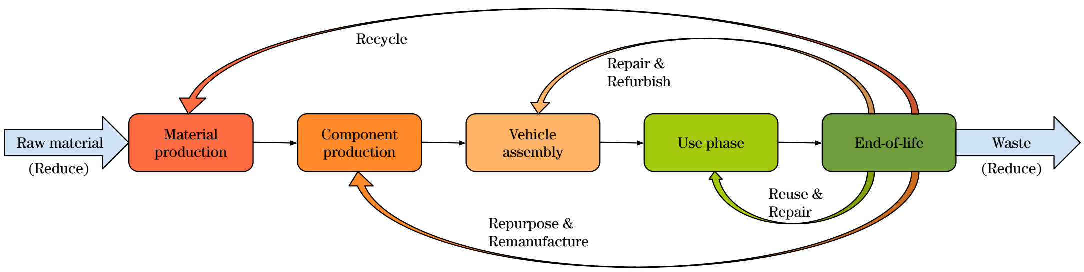

Figure 4.3: Circular life-cycle thinking applied to components in the automotive industry, from material production to end-of-life.

In the end-of-life step, the designers will be presented with a diagram to find standard recycling rates for the most common materials, combined with proposals for parts to reuse.

The recycling rates or amount of reused material can be used as inputs to create similar looking tables to the comparison but including end-of-life. The purpose is to increase the users understanding of the potential benefits of having effective and well-established end-of-life for vehicle components. Furthermore, it can also demonstrate for decision-makers on all environmental savings the company is currently missing. Figure 4.3 is available once again to remember about the resource life-extending strategies.

4.2 Results of the tool & conclusions from user

Results have been generated using the tool and are compiled in this chapter. Overall feedback on the tool is that it is easy to use and clear where to input values. The comparison tab is helpful to decide on the best component, partly thanks to the decision box giving a hint. The questionnaire is functional and makes it easier to understand how to increase the sustainability of a component. The end-of-life tab helps realise the end-of-life potential. However, they are a bit unsure of when to use it since they cannot guarantee what will happen to a component once it reaches end-of-life. The conclusions drawn by the designers during the final meeting when using the tool is split up in three subsections below.

4.2.1 Comparisons excluding end-of-life

For the first comparison, materials for the PMSM and PMaSynRM was entered and the methodology in section 3.2.4 was applied. Figure 4.4 shows the mid-point impact category climate change in the production and use phases. With a low CO_2 intensive-electricity mix in the use phase, the production phase contributes to the most significant impact in total. However, when the CO_2 intensity of the electricity mix is high, the use phase makes a considerable contribution to the total impact.

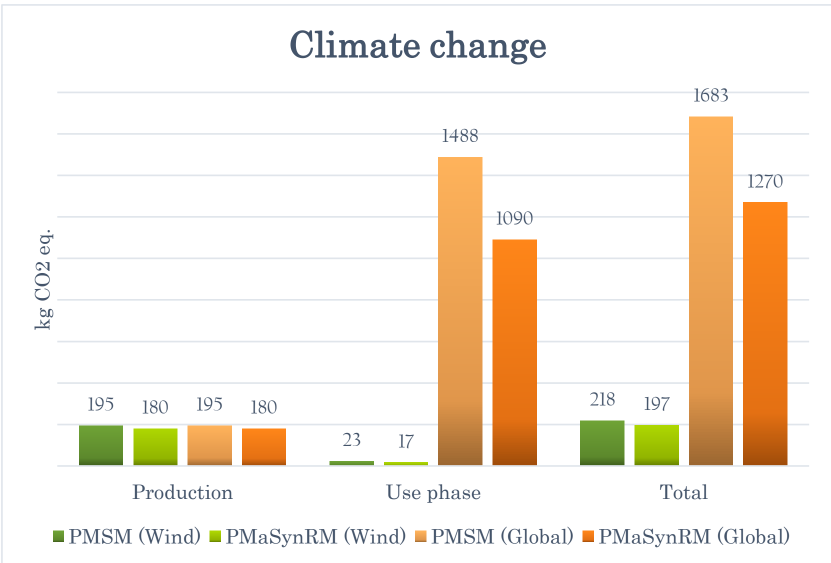

Figure 4.4: Two different EMs life-cycle impacts in the production and use phase with wind and global energy mixes, with Climate change in kg CO_2 eq.

The methodology described in section 3.2.3 was applied to gain user insights. The designer was able to conclude that when the global electricity mix was applied, that the PMaSynRM motor is superior in both the production and use phases. Further conclusions from the designer were, in order to lower the total emissions of CO_2 eq., he would try to improve the use phase by reducing the losses coupled to the motor. When the wind mix is selected the designer concluded that the PMaSynRM motor is beneficial in both the production and use phases, but the differences were now more minor in absolute values. To lower the total emissions of CO_2 eq., he would try to improve the production phase since most of the emissions occur by applying the principles in the questionnaire from sustainable materials and material efficiency.

Figure 4.5 shows the end-point impact category cost for society for the production and use phases. When the CO_2 intensity of the electricity mix is low, the production phase contribution is significant compared to the use phase. Similarly to when the climate change is analysed, the use phase contribution is important once the electricity mix's CO_2 intensity increases. However, the use phase is in the same magnitude as the production phase with a CO_2 intensive electricity mix, where the PMSM's use phase contribution is larger than its production phase, and vice versa for the PMaSynRM.

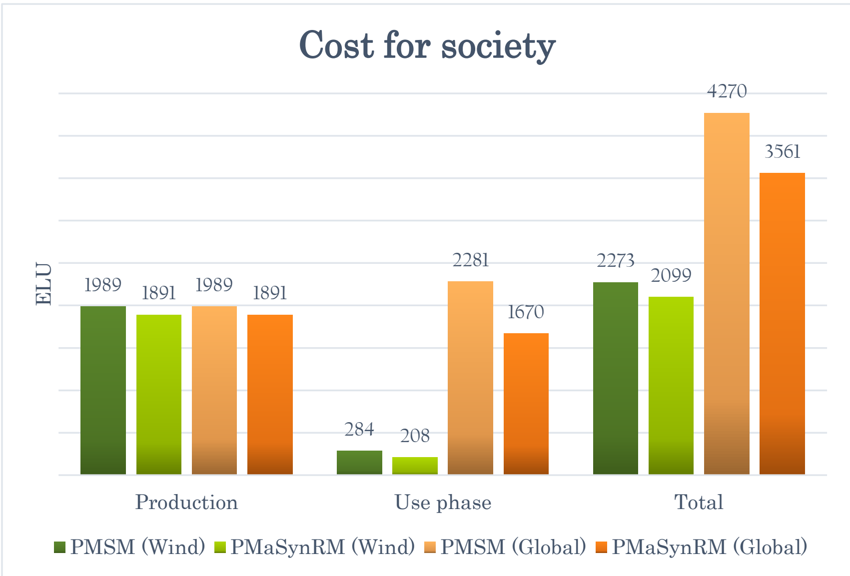

Figure 4.5: Two different EMs life-cycle impacts in the production and use phase with wind and global energy mixes, with Cost for society in ELU.

When the global mix is selected, the designer concluded that the PMaSynRM motor is superior in the use phase and marginally better in the production phase. To lower the cost for society, he would improve both the production and use phase. The production phase would be lowered by applying the principles in the questionnaire from sustainable materials and material efficiency. The impact in the use phase could be mitigated by reducing the energy usage of the motor. Once the wind electricity mix was selected, the designer concluded that the PMaSynRM motor is exceptional in the use phase and marginally better in the production phase. To lower the cost for society, he would try to lower the impact of the production phase. It would be lowered by applying the principles in the questionnaire from sustainable materials and material efficiency. The impact in the use phase would be mitigated by reducing the losses coupled to the motor.

4.2.2 Comparisons including end-of-life

For the next comparison, the same methodology as in the previous section was applied apart from certain assumptions regarding end-of-life. In Figure 4.6, the components are assumed to be reused due to uncertainties regarding material quality in the recycling process. This case of reuse is a best-case scenario where no further energy is necessary to reuse the component. The end-of-life phase cancels out the impacts from the production phase and results in a lower total impact than Figure 4.4. The results show that when the low carbon intensity electricity mix is applied, the total climate change impact allocated to the components is limited.

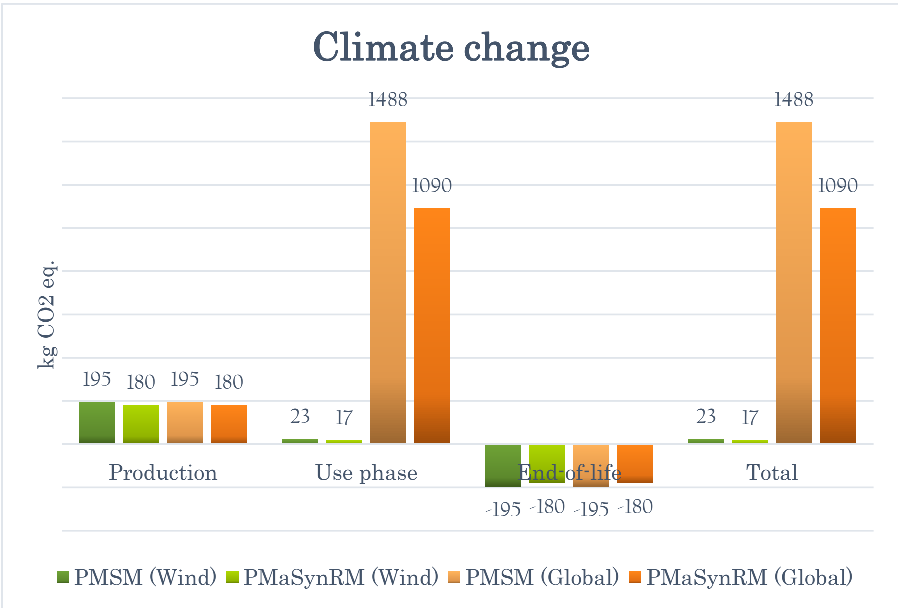

Figure 4.6: Two different EMs life-cycle impacts in production, use phase, and end-of-life with wind and global energy mixes, with Climate change in kg CO_2 eq.

Apart from the conclusions drawn when not considering end-of-life, the designer realised the potential of being able to secure a good end-of-life strategy. It is more beneficial to work with end-of-life once the climate change impact from the production starts getting more significant compared to the use phase. Alternatively, once the work put in to improve the use phase shows diminishing returns in energy usage.

Figure 4.7 was created on the same terms as Figure 4.6. In this case, the end-of-life phase cancels out the production phase and results in an overall lower cost for society compared to when end-of-life was not applied. This is where the strongest reaction was achieved from the designer, since being able to guarantee an efficient end-of-life for any of the electricity mixes would allow for a significant reduction of the total cost for society. Also, which component to choose would depend on its ability to attain sustainable end-of-life.

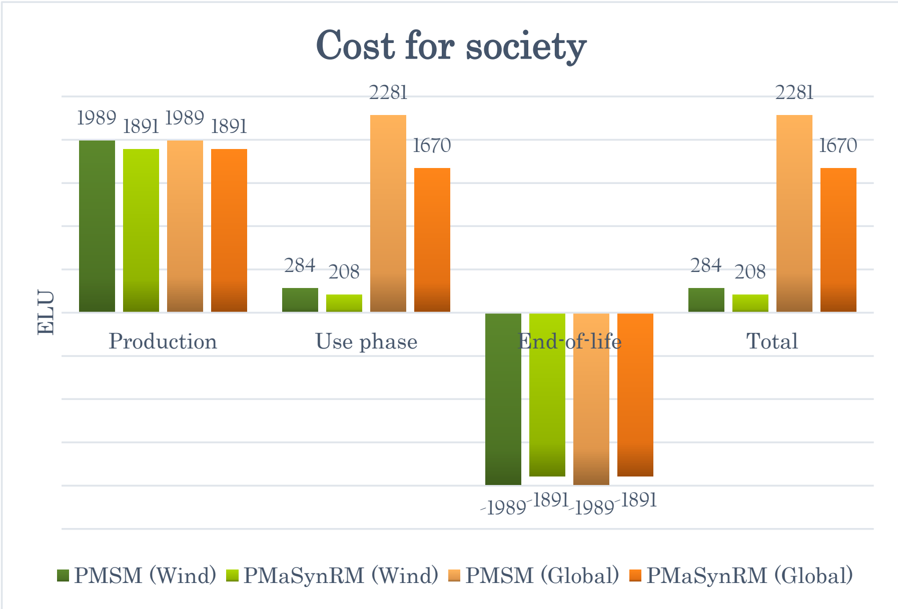

Figure 4.7: Two different EMs life-cycle impacts in the production, use phase, and end-of-life with wind and global energy mixes, with Cost for society in ELU.

5
Analysis

5.1 Tool analysis and accuracy

In this section, the resulting decisions using the tool with and without end-of-life will be discussed. The adaptations done to better suit the users together with the tool's accuracy will be handled as well.

5.1.1 Decisions without end-of-life

In Figure 4.4, it is possible to see that from a climate change perspective, the use phase needs to be improved if the global electricity mix is used. This electricity mix will be applicable in most cases since VCC has its largest market shares in China and the US (Volvo Car Corporation, n.d.-b). The wind electricity mix has a low CO_2 intensity and should be used as a futuristic scenario for countries at the forefront of sustainable energy generation.

Figure 4.5 gives a different picture of which life-cycle phase the problem lies in. Even if the global electricity mix is selected, the production phase is almost equal to or worse than the use phase. This highlights why it is important to monitor more than just CO_2 equivalents for a company to become sustainable (Volvo Car Corporation, n.d.-b). The high cost for society in the production phase is due to the widespread usage of copper in the copper windings of the EMs, which is highlighted by the literature as the most critical material to reduce (Tillman et al., 2020). The results suggest that it is worthwhile to start improving the production phase of the EMs today, and not within five to ten years as some might think. A reduction of copper will contribute to a cost-saving for the company.

These selected sustainability parameters can reflect the sustainability performance of EMs and potentially other EV components. The use of CO_2 equivalents makes it easier to assure that VCCs sustainability strategy is followed, even for projects in the early concept stages where no suppliers are set, thanks to generalised data for the calculations.

5.1.2 Decisions with end-of-life

Once the end-of-life is accounted for when looking from a climate change perspective, the production phase will be even more critical to improving (Figure 4.6). This might be seen as a completely irrelevant comparison because end-of-life can not cancel out the entire production. Applying the resource life-extending strategies reuse, repair, or refurbish, this is not such a lousy comparison because these strategies keep the component's quality very high, requiring only relatively small amounts of energy to be put back into the use phase. However, this does not mean the climate change impact is removed. Instead, it is allocated to the new vehicle or component where it is placed. It is also important to remember that the end-of-life is purely speculative in the tool and not for decision-making.

When looking at the cost for society, it shows that the end-of-life has even greater potential to improve the total impact (Figure 4.7). This shows more clearly why it is essential to start designing components for end-of-life and establishing adequate end-of-life facilities such as those Renault are currently using (Groupe Renault, n.d.-a). Furthermore, as one ELU is equal to one Euro, establishing these processes could result in considerable cost savings if companies have to start paying for the damages they are causing to society (IRP, 2019). This means that end-of-life could potentially halve the externalised cost for society. The results also show that the PMaSynRM is superior in all the comparisons done, which is in line with the research.

5.1.3 Adaptations to users

Firstly, the tool was created in Excel in order to make it familiar to all users. The simplicity allows anyone holding ownership of the tool to make changes and update data, ensuring the tool stays up-to-date. Each tab has been adapted only to contain the bare minimum number of inputs to gain valuable results. Inputs have been established with the users, and most cells have also gained an information box if any uncertainties arise.

Secondly, all inputs that could be hard to collect or understand for users with limited sustainability knowledge were excluded, e.g., country-specific emission factors for material production, manufacturing emissions of components, and transportation emissions during the life-cycle for materials. These inputs were also excluded since they did not significantly impact the results and conclusions when using the tool.

Finally, the tool provides a base for users to learn. The tools scope can grow together with the users' knowledge and be continuously adapted to new components. Also, the way end-of-life is implemented in the tool, where it is not necessary to gain a valuable result, allows novice users to ease into life-cycle thinking. It is also better adapted for users in the early concept stages with certain unknowns since it will always show a result. However, the certainty of those results could be worse.

5.1.4 Determining the accuracy

A thorough comparison shows that the tool does allow the same conclusions to be drawn as the research. The numbers are not identical in the tool and the article from Nordelöf et al. However, the same motor and life-cycle stages are indicated as having the highest environmental impact. The most important figure for the comparison is Figure 5.1, and Figure 4.4. By studying the Nd(Dy)FeB and PMaSynRM in 5.1, it is possible to see that when an electricity mix with low CO_2 intensity (Wind and Sweden) is reviewed, the production phase is the largest contributor. Even if Figure 4.4 says the use phase is significantly smaller, this is because the wind electricity mix has a lower CO_2 intensity than the Swedish mix has. The same conclusions would be drawn in this case, and the same EM would be chosen since the PMaSynRM is superior in the LCA from a climate change perspective. When looking at the CO_2 intensive mixes (Global and USA), the use phase becomes more significant than previously, and this is expected.

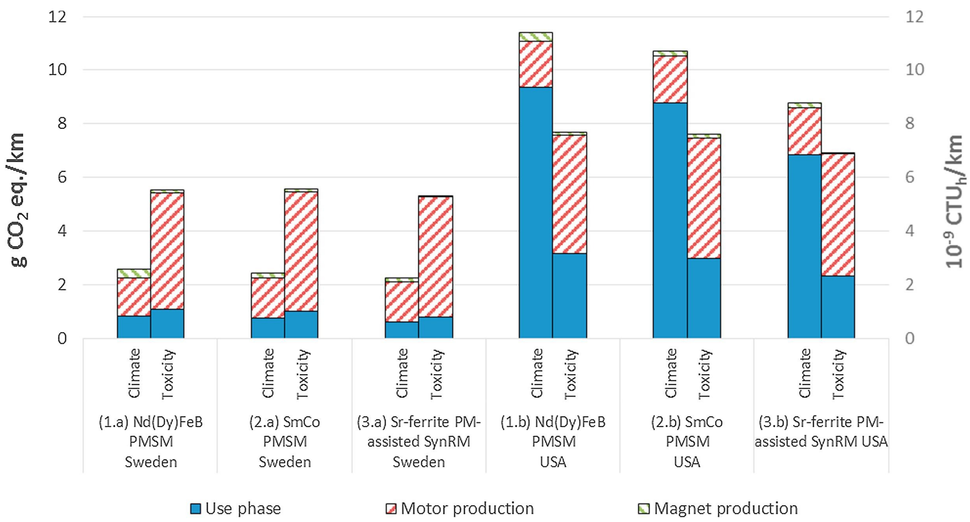

Figure 5.1: Results from the LCA of several EMs, (Nordelöf et al., 2019).

What is interesting to see in Figure 5.1 is that the production phase remains largely unchanged, even though the manufacturing steps of the EM have been considered in the LCA. This shows how small of an impact the manufacturing itself has and motivates the choice to leave it out of the tool. When looking closer at the Nd(Dy)FeB, the use phase stands for 82 % of the total climate change in Figure 5.1 from the LCA, and 88 % of the total climate change in Figure 4.4 from the tool. The PMaSynRM shows a similar difference with 78 % and 86 % in the respective order. There are several possible reasons for the difference, to mention two; the CO_2 intensity of the electricity mixes can differ, and the material data is not the same.

5.2 Users and circular life-cycle thinking

This section will discuss how the tool contributes to circular life-cycle thinking and its effect on the complexity of decisions.

5.2.1 The tool's contributions

By using the tool, the users can increase their life-cycle thinking and gain new perspectives. Previously, no sustainability data was readily available in such an early concept stage. The tool is hugely beneficial since more extensive changes are easier to do in the early stages of a new concept since fewer parts of the design is locked in as explained in Section 2.5.2.

The questionnaire allows the user to do a self-evaluation of their sustainability work. This is great for increasing their understanding of circular life-cycle thinking and gives them more self-independence when evaluating sustainability. It allows them to do a quick sustainability check whenever necessary or when management information is wanted. The questionnaire manages to catch perspectives that might have flown by unnoticed otherwise. The questionnaire applies sustainability knowledge on a component level and translates it to be relevant to people with limited sustainability knowledge. It enables sustainability thinking to evolve from reducing the amount of material and increasing efficiency to instead pointing at a specific material or rethink the entire design completely. Most importantly, the tool will allow all users to apply the same methodology when doing sustainability calculations, allowing them to get similar results. However, their conclusions might differ, but the tool will give them the same argumentative basis, allowing for discussions leading up to the same conclusions. In contrast, today, they use different data, looking at different parameters, leading to different results and different conclusions.

5.2.2 Complexity of decisions

Comparing costs and performance metrics have been done for a long time in the automotive industry, and it has always a balance between the two, where sustainability have not been prioritised (left in Figure 5.2). This led to sup-optimal decisions from a sustainability perspective due to the complexity of such decisions. Sustainability might have been taken into consideration in one form or another, however, with the tool (right in Figure 5.2) it is now possible to compare it just as the other measurable metrics, which TEEB highlighted the importance of (EC, n.d.-a). The drawback is that adding sustainability as another factor to be optimised can increase the complexity of the decisions. It is logical since bringing in more variables will make it more difficult to optimise, but finding and proving that an option is more or less sustainable is now possible. By studying Section 4.2, and comparing the designer's conclusions with those of the researchers, it is clear that the designer was able to draw the same conclusions, even aligning with the conclusions from the literature. In this case, though, it is important to remember that only sustainability was a criterion. When it is time to make a sustainable decision regarding what component to select, it is vital that sustainability is seen as equally important in the organisation as performance and cost.

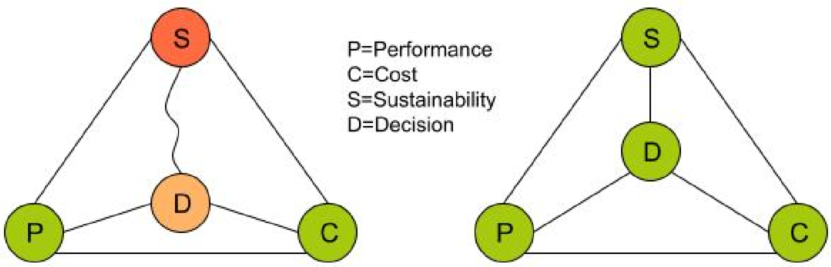

Figure 5.2: How the tool helps to optimise decisions from a sustainability, cost, and performance perspective.

The tool excels in motivating circular flows for components by demonstrating their potential in a working circular flow. By displaying the resource life-extending strategies and explaining why designing a product purely for recycling is not attractive, the tool motivates why it is essential to get the component back to the use phase as efficiently as possible. At some point, designers will realise the benefits of designing a component for a circular flow, rather than reducing the impacts from producing it and increasing the efficiency. What the tool does not help with, however, is what resource life-extending strategy should be applied. This will depend on what component is being examined since it may not be worthwhile designing a component for infinite reuse but rather re-manufacturing due to exponential material requirements. The decisions may be more straightforward once the tool gets expanded further to gain a more comprehensive system perspective. Some choices will be decided upon where there are varying degrees of certainty because some components can be examined using the tool, and others can not.

6
Discussion

6.1 Strengths and weaknesses

This section will discuss the strengths an weaknesses of the method used, the limitations and assumptions set up, the reliability and credibility of data used, and the applicability for this project.

6.1.1 Methodological choice

The method and outputs from the tool are adequately accurate to compare different components but should not be used to measure absolute impact values. However, they can give a perception of the magnitude of the values. It is possible to say that comparing two very advanced components but of the same type decreases the certainty of the results because of the uncertainties in the material data values. It is also important to remember that if the materials and quantities in the components are very similar, it matters less which component is chosen from a sustainability perspective in the production phase. Then it would come down to the energy usage in the use phase, where the calculations are less uncertain.

The values for the electricity mix can have a slight impact on the results since it is not entirely sure how the electricity mix will look in the future. However, the vehicles will theoretically use electricity with the same CO_2 intensity, making energy usage the only factor that matters. Accordingly, the researcher claims that the most uncertain case is when two less similar components are compared. E.g., when one component is substantially superior in the production phase and the other in the use phase, ending up close in the total. Then the expected lifetime of the component will become more critical, which can be further extended by guaranteeing efficient end-of-life using resource life-extending strategies. The ethical aspects can be complex to grasp for designers fully and put a score on. However, the questionnaire gives some guidance regarding ethical and social aspects combined with the EPS methodology.

6.1.2 Limitations and assumptions

What limits the tool's scope is the availability of information and the rapidly increasing knowledge necessary to use the tool when the scope extends. The most significant information limitations are the knowledge about the availability of materials the designers have to choose from when designing a product and the quality and reliability of data. To keep the data up to date is also a challenge, and automating this process will make it easier to add in more materials. However, doing so could potentially change the results of the analysis in the middle of the concept phase, making it harder to rely on the tool from a decision stand-point.

6.1.3 Reliability and credibility of data

There are different certainties of the material data used where steel, electrical steel, aluminium, copper, and plastics are of high quality and reliability. These are all common materials, and they are widely used, and lots of different data sets are available. Those with a lower certainty are REEs, e.g., Dy, Nd, and Tb. Electronics are also uncertain due to their varying material content. The problem with the lower certainty materials is that they can be hard to allocate due to them, in many cases not being the primary resources and a general lack of data and data-sets.

6.1.4 Applicability

As mentioned previously, the system perspective must remain since only using the tool for one specific component can negatively impact sustainability optimisation on a system level. A specific example could be the choice of a more sustainable EM that forces less sustainable PE, leading to a higher comparable total impact. However, the tool can be used for evaluating the sustainability of other components, such as PE. Collecting and allocating material data for components are the only barriers to applying the tool, including to other industries.

It is vital to collect material data for the components in the powertrain and then work outwards towards the affected systems. Having the tool work for one component initially could be advantageous. Since learning how to optimise one component before tackling system optimisations decreases the complexity of the optimisation, while the users are still learning more about sustainability, life-cycle thinking, and circular economy. Finally, the most significant future development of the tool is moving the end-of-life into the comparison itself. However, the only end-of-life process guaranteed for the EM is recycling, of which VCC does not hold ownership. By establishing their processes for end-of-life, VCC will be able to guarantee more efficient resource life-extending strategies being used.

6.2 Contribution to subject

This section will discuss how the work contributes to the subject area and strengthens it.

6.2.1 Added contribution

The project has made it possible for people previously disconnected from sustainability aspects to make informed decisions and understand the complexity of those decisions. The time required to compile information for the basis of a decision is also significantly shortened. Thereby, more frequent evaluations can be completed. There are EPS tools available, but these do not bring in the circularity aspects or help make decisions. The project has also contributed with an approximate and transparent value for externalised environmental costs, indicating how much of a cost the society absorbs and the importance of increased corporate responsibility.

6.2.2 Results contradicting or strengthening previous studies

There are not enough EPS studies available to compare the results to. However, the tool managed to highlight the important conclusions from Tillman et al. extended review of electric motors, where copper usage was considered one of the most if not the most critical aspect.

7 Conclusion

The main of the thesis have been fulfilled. It was to explore possibilities to use life-cycle thinking to increase resource efficiency early in the design process of electric vehicles. The aim was further to suggest what could be done to provide designers with data to make sound sustainable decisions for electric vehicle components. This was done by applying the EPS methodology and compressing it into a sustainability tool for electric motors. It was possible to calculate the externalised cost to society, greenhouse gas emissions, and human toxicity for the production, use phase, and end-of-life.

It has been concluded that a sustainability tool must contain easy to understand and relevant information, such as basic principles of circular economy and CO_2 emissions, to attain a life-cycle perspective. This will enable users to understand better the benefits of being able to provide efficient end-of-life.

It has also been concluded that only the significant environmental impact contributors can be included for a sustainability tool in the concept phase to stay accurate, allowing fewer inputs and a faster assessment process.

Further conclusions are that giving the users transparent data, results, and a suggestion for the best component reduces the complexity. It also allows the users to grow their sustainability knowledge and understanding continuously. Having an actual value for the sustainability performance makes it easier to prioritise and also reduces complexity.

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