

# Cutting emissions with remanufacturing

A comparative Life Cycle Assessment of Husqvarna's  
manufactured and remanufactured robotic lawn mowers

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# Cutting emissions with remanufacturing

A comparative Life Cycle Assessment of  
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robotic lawn mowers

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# Abstract

An increase in the use of natural resources is directly associated with an increased environmental impact. It is therefore of importance to lead the manufacturing industry towards a route of material efficiency. Remanufacturing is an industrial process that brings a used product and its components back to like-new or better condition. By avoiding manufacturing of new products, great savings in virgin material extraction and energy use can be achieved. The thesis aims to evaluate as well as compare the environmental effects of linear and circular production systems in hardware manufacturing sectors, using the case of a manufactured and remanufactured robotic lawn mower. Furthermore, potential benefits and disadvantages with remanufacturing are highlighted. The study is based on the lifecycle assessment (LCA) methodology. Data for the case study and the related processes in respective product systems was collected from scientific literature, interviews with relevant stakeholders, and from internal documents provided by the case company. A literature review was conducted to find potential benefits and disadvantages for original equipment manufacturers. The LCA results showed that remanufacturing of a robotic lawn mower contributes to lesser environmental impacts in terms of all chosen impact categories compared to a newly manufactured product. The findings are well supported by the literature which also points to the benefits of remanufacturing. The environmental benefits of remanufacturing are related to several contextual factors. The result of this thesis intends to shed more light on the pros and cons of remanufacturing, with the intent to better inform OEMs about remanufacture as a circular business model.

Keywords: Life cycle assessment, LCA, Remanufacturing, Resource efficiency, Circular economy, Electric and electronic equipment, Hardware manufacturing sector.



# Populärvetenskaplig sammanfattning

## Minska miljöpåverkan med återtillverkning!

*Tänk om du kunde bidra med en mindre miljöpåverkan i dina vardagliga val? Genom att välja en återtillverkad robotgräsklippare kan du minska din miljöpåverkan med 20–30%. Hur är detta möjligt och vad är egentligen återtillverkning?*

Produkter vi köper påverkar miljön under hela livscykeln, från produktion till omhändertagande av avfall. Flera studier har visat att en ökad användning av naturresurser är direkt förknippad med en ökad miljöpåverkan. En omställning till mer hållbara alternativ vore därför mer fördelaktigt för miljön. Ett alternativ för en mer hållbar konsumtion är återtillverkning. Återtillverkning är en process där man samlar in använda produkter och återställer deras kvalitet som att den vore ny. I den här processen produceras inte nytt material utan man tar tillvara på de material som redan är tillverkade och fixar det som behöver repareras eller bytas ut. Vore en återtillverkad produkt bättre miljömässigt jämfört med en nytillverkad? För att utvärdera vilket scenario som är att föredra ur ett miljöperspektiv utfördes studien med hjälp av en livscykelanalys (LCA). Anledningen till att en LCA-studie valdes är för att den här metoden är användbar för en miljömässig utvärdering av produkter. Den här studien har använt en robotgräsklippare för att jämföra om en återtillverkad produkt är bättre än en nytillverkad avseende miljöpåverkan. Resultatet visade att återtillverkning av en robotgräsklippare bidrar till en mindre miljöbelastning vid jämförelse med en nytillverkad produkt. Förutom att vara ett fördelaktigt alternativ för miljön visade även resultatet att människors hälsa påverkades mindre av en återtillverkad robotgräsklippare. Detta resultat stöds även av funnen vetenskaplig litteratur om återtillverkning. Hur stora fördelarna med återtillverkning är, är dock beroende på vilken produkt som undersöks samt vilken geografisk placering återtillverkarna har. Den sistnämnda anledningen beror på att en olämplig placering kan leda till alltför stora utsläpp från ökat antal transporter som krävs för att returnera de använda produkterna till återtillverkarna. Sammanfattningsvis så är återtillverkning ett bättre

alternativ jämfört med nytillverkning när det gäller en robotgräsklippares miljöpåverkan. Resultaten från denna uppsats kan vara användbara för både tillverkare och konsumenter som är villiga att byta till en hållbarare produktion eller konsumtion.

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Kind regards,  
Maja.





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# Abbreviations

AM550 – Automower 550  
CBM – Circular business model  
EEE – Electronic and electrical equipment  
ELCD – European life cycle database  
EOL – End of life  
FU – Functional unit  
GHG – Greenhouse gases  
GDP – Gross domestic product  
GWP – Global warming potential  
ILCD – International Life Cycle Data  
IPCC – Intergovernmental Panel on Climate Change  
ISO – International Organization for Standardization  
LCA – Life cycle assessment  
LCC – Life cycle costing  
LCI – Life cycle inventory  
LCIA – Life cycle impact assessment  
NDA – Non-disclosure agreement  
NMC – Lithium Nickel Manganese Cobalt Oxide battery  
OEM – Original equipment manufacturer  
PCB – Printed circuit board (board with a complete circuit)  
PWB – Printed wiring board (board without a complete circuit)  
RAM550 – Remanufactured Automower 550



# 1. Introduction

Most agree that the Earth has limited resources and the current linear model of modern economy, with its intensive material flows and waste generation, contributes excessively to global resource depletion (Lacy & Rutqvist, 2015) as well as other global impacts, such as climate change. In spite of relatively smaller share in the generation of GDP (Gross domestic product) in Europe, the manufacturing sectors are responsible for a significant part of energy consumption, material use and waste with significant impacts on the environment (Parker, et al., 2015). A linear economy can be defined as a one-way system, converting natural resources into waste through production and use. Environmental deterioration arises by continuously removing natural capital, which can result in loss of finite reserves (Murray, et al., 2017). The linear economy enhances anthropogenic impacts on the environment, contributing to climate change, loss of biodiversity and changes in the biogeochemical cycles (water, phosphorus, carbon, nitrogen). As an increase in the use of natural resources is directly associated with an increased environmental impact, it is important to implement circular flows into our society (Milios, et al. 2019a).

The concept of a circular economy builds on a framework with a long-time perspective where the focus is to maintain the value of products, materials and resources along with reducing waste (Geissdoerfer, et al., 2020; Nasr & Russel, 2018; EC, 2015). This concept has potential to aid the transition towards more circular systems if access to reusable, recyclable and renewable inputs are enhanced, and cleaner outputs with a lesser environmental burden are secured (Abad-Segura, et al., 2020; Lacy & Rutqvist, 2015). Indeed, with the current situation where a majority of the biogeochemical cycles has been altered by human activities (e.g., excessive release of carbon dioxide), circular flows are indispensable (Murray, et al., 2017).

As the environmental pressure has increased in the industries from international and national legislations, more focus has been directed to implementing circular business models (CBM) which focus on efficient resource utilization along with

minimizing waste and emissions (Geissdoerfer, et al., 2020; Rosa, et al., 2019). For instance, extending product and resource value through remanufacturing can be one of the important factors for achieving a circular economy by closing and slowing down resource flows (Bakker, et al. 2021; Kurilova-Palisaitiene et al., 2020; Milios, et al. 2019a; Guidat, et al., 2017). However, the advantages of the remanufacturing process depend on product characteristics and contextual factors of background systems (e.g., infrastructures, logistical solutions, regulatory frameworks). More case studies are needed in order to better understand how changes in manufacturing strategies can be cost-effective and environmentally efficient.

An original equipment manufacturer (OEM), Husqvarna, has expressed their interest in comparing the environmental impacts of a remanufactured robotic lawn mower to their manufactured counterpart. To effectively present the environmental performance of products, services and business model solutions, it is essential to evaluate the effects from a life cycle perspective (Norgate, et al., 2007). This perspective allows assessing critical stages in the supply chains (lifecycle) of product or service systems. A life cycle assessment (LCA) is a well-known tool for evaluating environmental impacts of the entire supply chain (Benedetto & Klemes, 2015; Čuček, et al., 2015). It is a “cradle-to-grave” analysis and by collecting and analyzing the sustainability performance data of the product, an LCA study can effectively highlight both the environmental benefits and impacts with remanufacturing (Čuček, et al., 2015).

This thesis aims elucidate on the environmental implications of circular product solutions. It is based on a company case and operationalizes a comparative LCA to compare a newly manufactured and a remanufactured product. By exploring and discussing the environmental implications of remanufacturing, the thesis intends to shed more light on the pros and cons of remanufacturing, with the intent to better inform OEMs about this circular business model.

## 1.1 Aim and research questions

The purpose of this thesis is to explore the environmental implications of remanufacturing and increase the understanding of the potential benefits and

impacts. The objective is to develop and test a model to evaluate as well as compare the environmental effects of linear and circular production systems in hardware manufacturing sectors. The focus is on the electric and electronic equipment (EEE) sector, exploring a case of Husqvarna and its robotic lawn mower alternatives – a newly manufactured and a remanufactured. The two product systems will be systematically compared on the basis of the LCA methodology. The study takes into account the specifics of the sector, product group and the company's business model.

Research questions to be answered are:

- I. Which environmental impact categories and indicators are relevant in an LCA model for remanufactured robotic lawn mowers?
- II. What are the environmental impacts of regular manufacturing and remanufacturing of used products?
- III. Which industrial processes, parts of the supply chain or design elements of product-specific business models are most important in terms of environmental performance?
- IV. Which benefits and disadvantages does remanufacturing bring for OEMs in the case of robotic lawn mowers?

## 1.2. Ethical considerations

A certain level of confidentiality is maintained in this study and agreed with the external supervisor, Jelena Kurilova-Palisaitiene, and the case company. A non-disclosure agreement (NDA) has been signed regarding the handling and disclosure of internal documents from Husqvarna. The outputs of the thesis will be made public, as per regulations of the Swedish Council for the Higher Education, pending a screening by the company.

The thesis involves gathering data and information via interviews based on voluntary participation. The interviewees will be, either verbally or by email, briefed



on all relevant aspects of the thesis and how the collected information is intended to be used.

The thesis is conducted in collaboration with the strategic innovation program RE:Source and Husqvarna. RE: Source focuses on developing circular, resource-efficient material flows to facilitate resource conservation by developing different aids for companies to invest in remanufacturing, e.g. a new RE:source initiative called Remometer. It is a tool for assessing the potential of remanufacturing of electrical products by measuring the economic, ecological and social benefits. It intends to support manufacturers with decision-supporting tools, aiding the development of circular business models. Furthermore, the results of this thesis will assist with relevant information for the project Remometer which is financed by Swedish Energy Agency, dnr 2019-021532, within the strategic innovation program RE:Source as well as for the case company Husqvarna. It will also partly contribute to the Swedish research program REES funded by Mistra.

## 2. Background

A used product does not necessarily need to be considered waste. The product, or parts of it, may be useful as remanufacturing material and ought to be reintroduced into the production process once again (Abad-Segura, et al., 2020). According to the British Standard BS8887-2-2009, which is one of the most recognized (Gustavsson, et al., 2021), remanufacturing is defined as such: “Returning a product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product.” (p. 35). The remanufactured product should, by the customer, be considered the same as a new product. The standard also involves the description of the remanufacturing process, which include dismantling the product, the restoration and replacement of components, and finally the testing of the product to ensure the quality and performance (Gustavsson, et al., 2021). Instead of producing a new merchandise, focusing on producing remanufactured products can result in less use of natural resources and the lifespan of the product could be extended (Bakker et al., 2021; Vogt Duberg, et al. 2020a; Kurilova-Palisaitiene et al., 2018). Some products with a low potential for technology obsolescence aided by standardized and compatible components, can be regarded as a valuable resource to enable and exploit the benefits of remanufacturing or other circular solutions. However, both the incentives and the initiatives to invest in remanufacturing are few even though several studies have argued for various environmental and economic benefits (Bakker et al., 2021; Vogt Duberg, et al., 2020a; Kurilova-Palisaitiene et al., 2020).

According to Lindahl, et al. (2006) there are three major incentives for OEMs to consider remanufacturing: environmental benefits, market demand and legislation. Remanufacturing is a recognized strategy for closing and slowing down resource flows in a product system (Guidat, et al., 2017). By excluding the production from the product system, which results in the extraction of limited natural resources, excessive energy use and unproductive waste generation, the theory is that the environmental load will be lesser for a remanufactured product compared to their manufactured

counterpart. Several studies of different products have in terms of environmental impacts, presented results where the manufactured object of study performs worse by comparison with remanufacturing (Peters, 2016; Liu, et al., 2014; Zanghelini, et al., 2014; Biswas, et al., 2013). In addition to environmental benefits, remanufacturing has also proven to be beneficial in an economic aspect as well (Kurilova-Palisaitiene et al., 2020; Vogt Duberg et al., 2020b; Kaya, 2010). OEMs can achieve an economic benefit with removed production costs which includes labor, energy use and materials. Even the cost of disposal will decrease. This means that remanufacturing can bring a significant economic contribution to the OEMs (Liu, et al., 2014; Kaya, 2010). Furthermore, a lower production cost implies that remanufactured products can have price advantages which is beneficial for increasing customers' willingness to pay (Kabel, et al., 2020). Remanufacturing can also contribute to a more developed product control through its entire life cycle. According to Kurilova-Palisaitiene et al. (2020), the companies can gain a higher total income from the remanufactured product (in addition to the normal production), protect intellectual property, increase their market share along with expanding the aftermarket sales by providing spare parts. Further positive aspects of implementing a remanufacturing process are that it can also improve the brand, increase customer loyalty and improve product knowledge as well as the products performance (Kurilova-Palisaitiene et al., 2020). Contrary to the environmental benefits with remanufacturing presented above, Lindahl, et al. (2006) argue that the implementation may result in excessive emissions from increased number of transports required to return the cores to the manufacturing plants. Furthermore, it is an issue that may also have a significant impact on the profitability for the company in regard to the costs of the investment (Vogt Duberg, et al., 2020b). The collection of used products is a critical part of the remanufacturing system and in order for it to be cost-effective as well as efficient for the OEM, appropriate collection strategies need to be evaluated and implemented. An issue associated with the collection is where to establish the location for the remanufacturing process (Vogt Duberg, et al., 2020b). Further uncertainties for OEMs are related to the supply of used products and their timing of arrival after collection from the customer (Vogt Duberg, et al., 2020b; Milios, et al., 2019b; Lundmark, et al., 2009). As there is no standardization for the lead time of remanufacturing operations it is difficult to estimate accurately. In this sense, the benefits from remanufacturing are exceedingly related to the context of study and its location (Lindahl, et al., 2006).

A thriving business involves an existing market and customer demand to maintain economic sustainable operations. A recent study presented that countries with developed remanufacturing markets did also have an extensive end-of-life (EOL) regulation (Guidat, et al., 2017). In accordance with Lindahl, et al. (2006), Guidat, et al. (2017) also considered legislation to be an important incentive to support the remanufacturing sector. For instance, Europe has a comprehensive framework of laws regarding industrial environmental management (Guidat, et al., 2017; Kaya, 2010). Legislation that supports remanufacturing are the directives on Eco-design Requirements for Energy-using Products (2005/32/EC) with the aim of energy efficiency improvement and the Waste Framework Directive (2008/98/CE) with classified EOL strategies. Even if there is no legislation that directly supports remanufacturing in wording (Gustavsson, et al., 2021), it can be considered an aid for OEMs to comply with these environmental regulations by leading the manufacturing industry towards a route of material and energy efficiency (Kurilova-Palisaitiene et al., 2020; Guidat, et al., 2017). Furthermore, Gustavsson, et al. (2021) concluded that remanufacturers of energy-related products are likely to be considered as manufacturers in the Ecodesign Directive.

The remanufacturing industry within EU is limited to a few industries such as heavy vehicles, automotive along with IT, and the Swedish sector constitute to less than 1 % of this (Kurilova-Palisaitiene et al., 2020). This means that the access to different remanufactured products is limited, and the Swedish consumers' acceptance is therefore considered inadequate (Kabel, et al., 2020; Kurilova-Palisaitiene et al., 2020; Milios & Matsumoto, 2019). Parker, et al. (2015) presents that the implementation of a remanufacturing process has been particularly successful for business-to-business sectors. However, among the general customer apparent aversion to buying remanufactured products has been observed (Milios & Matsumoto, 2019). The customer demand is an important factor in order for OEMs to consider remanufacturing. Therefore, it is essential to know the customers' perception of remanufactured products (Milios, et al., 2019b). A study conducted on consumer purchase intention of remanufactured robotic lawn mowers in Sweden claims that expected product quality and perceived risk, influenced by attitude towards remanufactured products, were the greatest areas of concern for the general customer (Kabel, et al., 2020). The customers' acceptance of remanufactured products is partly associated with the uncertainty of the quality performance and partly to ignorance.

There is an identified knowledge gap among customers in Sweden regarding remanufactured products (Kabel, et al., 2020). Similar results were presented by Milios & Matsumoto (2019), the findings showed that some of the consumers' perceived risks were linked to the knowledge of the product and perception of quality. The higher the knowledge and perception was among customers, the higher was their willingness to pay for the remanufactured product (Milios & Matsumoto, 2019).

## 3. Method

To answer presented research questions and achieve the aim of the thesis, an LCA for a specific case study has been conducted.

### 3.1 Case study research

One of the intended uses of an LCA is to highlight relevant and important environmental aspects related to a specific product system. In order to test the proposed method for selecting suitable environmental assessment indicators for EEE products, an instrumental case study was chosen as the research approach. An instrumental case study is when the chosen case is representative for other products, systems or services, which allows investigation of a certain issue rather than the specific product. This approach will be able to generate an in-depth perception of a complex problem in a real-life context (Yin, 2014; Crowe, et al., 2011; Stake, 1995). Reproducibility will be achieved by transparent documentation of every step made in the LCA (Yin, 2014). By the way of explanation, the results of the conducted LCA will be exclusively for the chosen case but the method presented will be general for other EEE products. In the thesis, a robotic lawn mower (type AM550) is to be the representative case (figure 1). The issue to be investigated is whether, and to which extent, there is a difference in environmental impacts between regular manufacturing of new products and remanufacturing of used cores.



*Figure 1. Picture of Husqvarna's Automower 550, the object of the study. Source: Husqvarna*

Two scenarios with different systems but with the same functional unit will therefore be compared. Scenario 1 will describe the current system, as in the regular manufacturing of new products (AM550) and scenario 2 will describe the system with remanufacturing of used cores (RAM550).

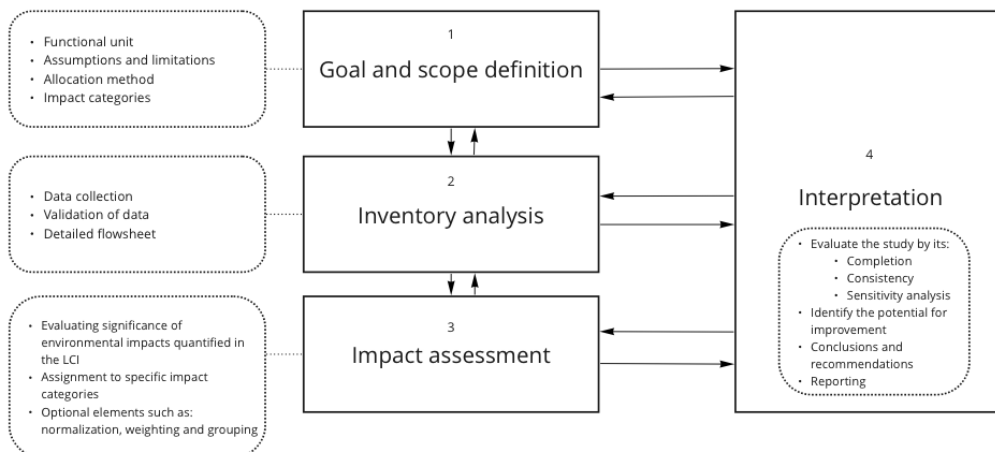
## 3.2 Life Cycle Assessment

Environmental impacts of a product or service can usually be defined by a life cycle assessment. The LCA study is an environmental system analysis method that addresses the use of resources and the environmental consequences of emissions throughout a product's life cycle (cradle-to-grave) (Benedetto & Klemeš, 2015; Čuček, et al., 2015; Rebitzer, et al., 2004). To conduct an LCA, the chosen case is modelled. The manufacturing process, remanufacturing process, usage and disposal of the product involves a complex reality with seemingly endless loops and subprocesses. A model is a simplification of complex systems which means that there will be distortions to reality to some extent (Goedkoop et al., 2016). The LCA model was conducted using the LCA software SimaPro 9.1.1.1., which is an environmental system analysis tool, and databases such as Ecoinvent and ELCD (European life cycle database) were used.

There is no certain methodology specified to perform an LCA. The International Standard Organization (ISO) has developed a framework and guidelines from various methodologies and approaches but no technique in detail is presented for each phase. According to ISO 14044, an LCA study consists of four phases: the goal and scope

definition, the inventory analysis, the impact assessment and the interpretation phase (figure 2) (ISO 14040:2006). The LCA conducted in the thesis will be made in accordance with the ISO framework, which is illustrated in figure 2.

Figure 2. The four stages developed by ISO and their applications (adapted from Čuček, et al.,



2015 and Rebitzer, et al., 2004).

In general, there are two types of LCA studies: attributional and consequential LCA. The methodological choice between attributional and consequential is dependent on the goal of the study as they answer different questions along with depicting the way the product system is to be modelled (Ekvall, 2020; Tillman, 2010; Rebitzer, et al., 2004). The definition of an attributional approach is that the LCA aims to describe relevant environmental physical flows to and from a life cycle and its associated subsystems (Ekvall, 2020; Finnveden, et al., 2009). It gives an estimation of how much of the global environmental impact is associated with the chosen case (Ekvall, 2020) and indirect effects are not studied. On the other hand, the definition of the consequential approach is that the LCA aims to describe how the relevant environmental physical flows will change in response to possible decisions or actions (Ekvall, 2020; Finnveden, et al., 2009). In other words, it is an estimation of how much of the global environmental impact is associated with the production and usage of the chosen case (Ekvall, 2020) and indirect effects, such as negative and positive feedbacks as well as market effects, are included.

It is argued that a consequential LCA gives a more precise result to which extent a contemplated action or decision really leads to a reduced environmental impact, as



this approach has been deemed to provide more information (Ekvall, 2020; Goedkoop, et al., 2016; Tillman, 2010; Finnveden, et al., 2009). However, this approach may not be feasible as it is data-intensive and the limited supply of marginal data in the accessible databases prevents an accurate result. Conducting an attributional LCA might give a more detailed and comprehensive result compared to a similar conducted consequential LCA, as it will probably be unfeasible to carry through (Ekvall, 2020). By the explanation above, an attributional LCA will be conducted.

The following subsections describe and explain the content of the four phases, following an attributional approach.

### **3.2.1 Goal and scope definition**

The goal and scope definition phase is the first subjective stage where the aim of the study, the intended audience, the reason for conducting the study and the system boundaries are specified (Goedkoop et al., 2016; EC, et al., 2010). Additionally, the goal definition should include whether the results of the LCA state “a comparative assertion intended to be disclosed to the public” (p. 34) as well as who commissioned the study (EC, et al., 2010). Furthermore, the functional unit, allocation method, impact categories and limitations due to assumptions as well as choice of method are discussed and set at this phase.

As previously declared in the aim of the thesis, the goal of this life cycle assessment is to generate an insight on the environmental impacts of a remanufactured robotic lawn mower along its supply chain. Further, the aim is also to present a result whether, and to what extent, the environmental impacts differ between a remanufactured and a manufactured robotic lawn mower.

The purpose of the LCA is to illustrate and explain the possible environmental benefits and impacts of remanufacturing EEE products, using the case of Husqvarna’s robotic lawn mower (AM550). The thesis is conducted in collaboration with the project Remometer and Husqvarna, and the results are therefore primarily intended for their use.

### 3.2.1.1 *Functional unit*

The functional unit (FU) enables a comparative study of two products, provided that the functional unit is the same for both the manufactured and remanufactured robotic lawn mower (Benedetto & Klemeš, 2015; Rebitzer, et al., 2004; EC, et al., 2010). The functional unit is defined as the cutting services provided by the robotic lawn mower over the timespan of 41 200 working hours. Both the remanufactured and manufactured product are assumed to be able to execute the same work, which is cutting an average grass lawn in Sweden for its entire lifetime of 8 years. Through remanufacturing, the lifespan of the robotic lawn mower is extended by four years. The assumption is that the robotic lawn mower is only used during the cutting season (approximately 25 weeks).

### 3.2.1.2 *System boundaries*

Aforementioned, a product system can be a complex reality. Not all inputs and outputs can be included if the LCA is to be manageable. The system boundary defines what should be included in the life cycle and which processes that belongs to it (EC, et al., 2010). System boundaries have to be well justified. Assumption and decisions such as system cut-off have to be validated by a sensitivity analysis. For a comparative assertion it is important to ensure equivalence of both product systems.

The current business model for a remanufacturing system at Husqvarna is applied in a pilot study<sup>1,3</sup>. From earlier studies of potential locations for remanufacturing robotic lawn mowers, it was deemed that a decentralized location (retailers) was one of the more economically feasible options in regard to a small-scale operation (Vogt Duberg, et al., 2020b). Therefore, the LCA model in the thesis aims to follow the current applied business model for scenario 2, which means that the used core is transported back to the retailer, the remanufacturing process occur, and the remanufactured product is then sold again.

The system boundaries and the allocation applied in the LCA model will follow an attributional approach. Life cycle phases included in the model are the production, remanufacturing, distribution, usage and disposal of the product, in other words, the whole supply chain. To compare the environmental impacts of different systems in relation to the FU, considerations are made regarding the emissions related to the original AM550 in the remanufactured supply chain. In order to fulfill the functional unit, the robotic lawn mower need to be able to function for 12 years. A

remanufactured product has a lifespan of 12 years and therefore, only one product is needed to fulfill the FU. A realistic assumption regarding the extended lifespan, which is 4 years, was based on communication with Husqvarna<sup>1</sup>. As a newly manufactured only has a lifespan of 8 years, one more is required. However, to fulfill the FU, only half of the 8 years of the second newly manufactured product is needed. Accordingly, the LCA will contain one and a half (1,5) successive life cycles of a new product and the life cycle of a (1) used core that intends to be remanufactured.

The ambition is to develop a model with as little influence as possible in the system boundary, albeit some activities had to be excluded. For instance, the pallet for AM550 is included in multiple other life cycles of other products and as it will not be delivered to the end customer, it will not be included in either life cycle of the scenarios (Tollin, et al., 2019). For scenario 2, the electronic equipment (rechargeable screwdriver) used by the retailers will not be included for the same reason as above along with that the environmental contribution of this equipment is assumed to be insignificant. Furthermore, no data could be obtained regarding incoming packaging materials at the manufacturing plant from the suppliers. As Tollin, et al. (2019) depicted, the contribution of these packaging materials to the overall environmental load is not significant and can therefore be excluded from the LCA calculations. Likewise, the loose part kit that comes with the robotic lawn mower is excluded in the calculations.

Some phases in respective life cycle are assumed to be the same. Most of the transport distances are assumed to be the same. Likewise, the energy consumption during use is assumed to be identical for both scenarios. All noted use of natural resources and emissions related to air, water and soil are included in the system boundaries.

*3.2.1.3 Technical specifications of the AM550*

The lifetime of the AM550 is assumed to be 8 years in the LCA model (table 1). In order to calculate the energy consumption during the product’s entire lifespan, the number of working hours need to be considered.

*Table 1. Assumptions regarding time and use for both scenarios (adapted from Tollin, et al., 2019).*

<i>Parameter</i>	<i>Quantity</i>	<i>Unit</i>
------------------	-----------------	-------------

<i>Lifespan</i>	8	years
<i>Weight</i>	23	kg
<i>Charging time</i>	60	min
<i>Cutting time</i>	270	min
<i>Rated power</i>	0.03	kW
<i>Efficiency factor</i>	0.85	

The robotic lawn mower can cut 5 000 m<sup>2</sup> by charging and cutting for one week. The assumption is that the AM550 is able to cut the grass for 4,5 hours and then requires recharging for one hour (Tollin, et al., 2019). This corresponds to 5,5 hours per cutting/charging cycle. In regard to the battery efficiency, charge and discharge losses are accounted for by adding 10 % in the calculation and it is presumed that full recharging occurs then the battery is completely depleted. The total number of charging/cutting cycles for 24 hours is 4,36 charging/cutting cycles per day. The total number of working hours can be calculated as such:

$$H_{tot} (h) = C_{day} \times w \times C_{charge}(h) \times C_{season}(\text{weeks}) \times l (\text{years}) \quad (1)$$

Where  $H_{tot}$  equals the total working hours of AM550,  $C_{day}$  is charging/cutting cycle per day,  $w$  is days per week,  $C_{charge}$  is cutting time per charge,  $C_{season}$  is cutting season and  $l$  is the lifetime of the lawnmower. With the result of the total number of working hours, the energy consumption can be calculated:

$$E (\text{kWh}) = \frac{H_{tot} (h) \times R_p (\text{kW}) \times 1,1}{E_f} \quad (2)$$

There  $E$  is the energy consumption,  $H_{tot}$  is the total working hours of the AM550,  $R_p$  is the rated power for an AM550 and  $E_f$  is the efficiency factor.

#### 3.2.1.4 Allocation

With a remanufacturing system, used material can directly substitute the input material in the production phase (Nicholson, et al., 2009) Thus, the studied product

system is credited with an avoided production of raw material through system expansion (Nicholson, et al., 2009; Baumann & Tillman, 2004). However, the environmental burden needs to be allocated at the end-of-life (EOL) phase of the robotic lawn mower as the product can either be transported to waste treatment or to remanufacturing. In a larger scale, this is dependent on the collection rate of used cores along with the amount of these that are functional for remanufacturing. As the LCA model follows the currently applied business model, as in a customer either buy, return or dispose of one robotic AM550, the assumption is that 100 % of the product in scenario 2 proceed to the remanufacturing process. However, set in a larger and more realistic scenario, not all robotic lawn mowers that are sold will proceed to be remanufactured. The scrap rate for a RAM550 can be researched in future studies, with this business model set in a larger perspective. In the EOL phase, the generated waste can either be recycled, incinerated or landfilled. In regard to the recyclable materials, the product only carries the environmental burden to the point there the material enters the recycling process.

Used in the SimaPro software, is the method “allocation at the point of substitution – unit (APOS)” and is therefore in the LCA calculations throughout the life cycle. This method considers recyclable materials to be by-products of the life cycle where it is generated and waste flows can be converted into useful products, for example, incineration of plastics can be modelled as energy recovery (Ekvall, et al., 2020). How the amount of impact is distributed is based on revenues of the product and the recycled material (Weidema et al. 2013).

#### *3.2.1.5 Impact categories*

In general, there are three broad groups of impact categories that should be considered: resource use, human health consequences and ecological consequences (Pennington, et al., 2004). An impact category can be defined as a group that represents a type of environmental problems. Through classification, the life cycle inventory (LCI) results are assigned to a selected impact category according to known substances’ characteristics and induced environmental issues (Hauschild, et al., 2013; Finnveden, et al., 2009; Finnveden, et al., 1999). The selection of impact categories should be comprehensive enough to cover the essential environmental impact related to the object of study along with being consistent with the goal (EC, et al., 2010). Impact

categories are generally divided into either midpoint-oriented or end-point-oriented categories (figure 3).

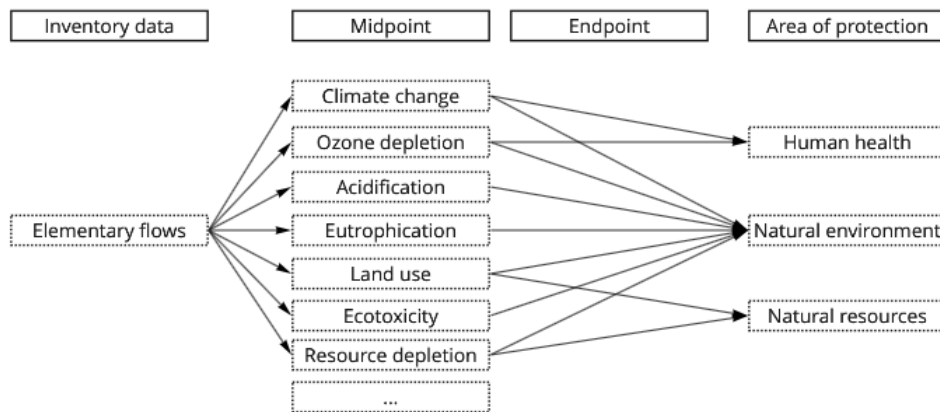


Figure 3. Illustrative overview how the characterization links elementary flows to midpoint and endpoint impact categories and then later to the main areas of protection (adapted from Hauschild, et al., 2013 & EC, et al., 2010).

A midpoint-oriented indicator defined by Hauschild, et al. (2013) is “an indicator placed at the location in the impact pathway up to which a common mechanism exists for the main contributing substances within that specific impact category” (p. 685). For instance, the midpoint indicator chosen for climate change will be at the point where the atmospheric radiation is increased. The cause of this impact is greenhouse gases (GHG) and to this chosen point, the pathway for respective gas is different. However, after the chosen location their impact is identical all the way to the areas of protection (Hauschild, et al., 2013). Contrary to this, endpoint-oriented indicators illustrate the impacts with direct societal concern, such as human life span, natural resources, valuable ecosystems, fossil fuels and mineral ores and so forth (Finnveden, et al., 1999).

In order to be consistent with the goal, the midpoint indicator global warming potential (GWP) is chosen as the main impact category. This is because the case company is interested to explore the difference in carbon dioxide emissions

contributing to climate change between the two products<sup>1</sup>. However, only including climate change in the analysis will give the overall environmental load of the products a limited impact coverage. For instance, the remanufactured robotic lawn mower may perform better in terms of GWP yet worse in acidification. The ambition is therefore to include more impact categories by exploiting a life cycle impact assessment method with an adequate impact coverage.

### **3.2.2 Inventory analysis**

The aim of a life cycle inventory analysis is to measure the quantities of various resources, emissions and waste generated per functional unit (Čuček, et al., 2015; Rebitzer, et al., 2004). Gathered data and information for the chosen case and the related processes in respective product systems was collected from scientific literature, interviews with relevant stakeholders (appendix IV), as well as from databases such as Ecoinvent, among others. Furthermore, specific data for each individual part regarding the materials, processes, locations and transportations related to the AM550, refers to the Bill of Material as well as the LCA conducted by Ramboll (Tollin, et al. 2019), which was provided by Husqvarna. This was all modelled in an LCA, using the LCA software SimaPro Classroom 9.1.1.1.

The LCI requires a great amount of data (Finnveden, et al., 2009), and there will be some data missing. The reasons are that some of the environmental data is documented on an organizational level rather than on a functional level as well as that the data for a unit process contains specific information related to proprietary technological data, which is considered sensitive information by the provider (Rebitzer, et al., 2004). In case of missing specific data from the OEMs/suppliers, generic data is used instead and will be based on a qualified assumption.

### **3.2.3 Impact assessment**

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<sup>1</sup> Jonas Willaredt, Vice President of Sustainability Affairs, Husqvarna AB, personal communication, 2021-04-01.

A life cycle impact assessment (LCIA) method is a compilation of characterization factors, each addressing their respective impact category (Hauschild, et al. 2013). The aim of a LCIA is to understand and evaluate the consequences as well as the environmental significance of the studied product system (Goedkoop, et al., 2016; Finnveden, et al., 2009). According to ISO 14040/44, are classification and characterization two mandatory steps that needs to be included if the study is to be referred to as an LCA. As mentioned in the impact category section, classification assign elementary flows (LCI) to the impact categories they contribute to (Finnveden, et al., 2009). Characterization involves multiplying the LCI data with the characterization factor for respective substance in order to illustrate the relative environmental impact contribution to each impact category (Finnveden, et al, 2009; Pennington, et al., 2004). There are various applicable methods and the selection is dependent on the goal of the study along with the chosen impact categories. As climate change is the primary focus, the GWP method published by the Intergovernmental Panel on Climate Change (IPCC) (Forster et al. 2007) will be applied. According to a study conducted by Hauschild, et al. (2013), which evaluated existing LCIA methods and characterization factors, IPCC 2007 GWP 100a is updated, scientifically robust and has the uncertainties described and calculated. The method can be applied with different timespans: 20, 100 or 500 years. This LCIA will use the 100-year timespan as both Tollin, et al. (2019) and Hauschild, et al. (2013) deemed it to be the best available.

In order to present a greater impact coverage, the method IMPACT 2002+ has been applied in this case. This methodology links the LCI data results through 15 midpoint categories and to four end point categories and is deemed valid by the ILCD (International Life Cycle Data) Handbook (2010). For IMPACT 2002+, which is a method with several different impact categories with respective characterization factors, normalization may facilitate the interpretation of the results and make the impact categories comparable with equal units (Goedkoop, et al., 2016; Pennington, et al., 2004). Normalization can illustrate the relative importance of an impact category by summarizing each one and divide them with a reference value (Finnveden et al., 1999).



### **3.2.4 Interpretation of the study**

At this phase, the results are evaluated and presented to answer the questions set in the goal definition (EC, et al., 2010), or in the thesis, the research questions. In order to highlight the significant issues such as key processes and elementary flows, a contribution analysis was conducted. Furthermore, a sensitivity analysis was conducted in order to validate the results. Due to the assumptions and limitations made in the LCA study, uncertainties are inevitable (EC, et al., 2010). The variables considered sensitive were the assumptions that may influence the comparative result and covers:

- Exchanged parts in the remanufacturing process
- Lifespan of a robotic lawn mower
- Number of times the remanufacturing process can occur

Lastly, the interpretation phase intends to collect and analyze the findings of the LCA study and in the light of the final result, draw conclusions and present recommendations (EC, et al., 2010).

## 4. Results

The results of the LCA model addressed above is presented in this chapter. For the LCI results, two scenarios with different systems but with the same functional unit, system boundaries, assumptions and methodological choices are presented in detail. Scenario 1 will describe the current system, as in the regular manufacturing of new products and scenario 2 will describe the system with remanufacturing of used cores. The results of the LCIA presents the comparison between a manufactured and a remanufactured AM550 with regards to their environmental impacts throughout the entire life cycle, using the impact methods IPCC 2007 GWP 100a and Impact 2002+.

### 4.1. Life cycle inventory analysis

The collected product-specific information is presented in this section and the process flowchart of the two scenarios is illustrated in figure 4. To present the input data of each phase will facilitate the reproducibility along with providing a better understanding of the LCIA results. Assumptions and limitations made in the life cycle inventory phase are presented here as well.



Figure 4. Process flowchart of the robotic lawn mower AM550, cradle-to-grave, with the remanufacturing process. Processes with dashed lines are excluded from the analysis.

#### 4.1.1. Scenario 1

The LCA model for scenario 1 includes all processes related to the production of the materials, transportations, usage as well as the EOL-management of a 23 kg AM550. The studied product system for the manufactured AM550 describes the current system, as in the regular manufacturing of new products.

##### *Production*

The required components are delivered to Husqvarna's manufacturing plant in Aycliffe (United Kingdom), by suppliers that have extracted and processed the

necessary raw materials. These components are then assembled and partly processed at the manufacturing plant. The processes occurring here is injection moldings of plastic parts which requires energy and generate waste (Vogt Duberg, et al., 2020b; Tollin, et al., 2019).

The manufacturing of one unit of a robotic lawn mower requires a total of 23,4 kWh for the injection molding and 1,4 kWh liquefied petroleum gas for forklifts (Tollin, et al., 2019). The components can be divided into seven different groups of material: body, chassis (top), chassis (bottom), cutting system, wheel (front), wheel (rear) and charging station (table 2).

Table 2. Main parts in a robotic lawn mower and its accompanying charging station. The main parts' respective materials and weights are presented as well. Due to rounding and exclusion of the documentation system, packaging and the loose part kit, the values do not add up to 23 kg.

Part	Body	Chassis (top)	Chassis (bottom)	Cutting system	Wheel (front)	Wheel (rear)	Charging station
Weight (kg)	3.33	2.15	5.53	1.2	0.99	0.5	3.7
Material							
Stainless steel	x	x	x	x	x		x
Steel	x	x	x	x	x	x	x
Plastic	x	x	x	x	x	x	x
Elastomers	x		x		x	x	
Electronics	x	x	x				x
Copper			x	x			
Aluminum	x		x	x			
PWB		x					x
Other metals*	x	x	x	x			x

\*Other metals include tin, neodymium, red brass.

Different datasets were considered regarding the battery cells. No specific production data regarding the details of the battery cells could be provided, and generic data had to be used in the LCA model. The information gathered was that the specific battery currently adapted is NMC batteries, Lithium Nickel Manganese Cobalt Oxide, type

18650 ~2,58 Ah (Tollin, et al., 2019). As no LCA-data regarding this type of battery could be found in available databases, a literature search was performed in order to supply the LCA model with representative data. The results of the literature search found representative data in an LCA of NMC batteries for electric passenger vehicles, NMC622 ( $\text{LiNi}_{0,6}\text{Mn}_{0,2}\text{Co}_{0,2}\text{O}_2$ ) battery, type 18650 (Sun, et al., 2020). It is assumed that the NMC battery cell used in the AM550 has the same metal-ratio (622) as the cell in Sun, et al. (2020), as this is one of the more commonly produced batteries in China (Sun, et al., 2020). The two battery types are similar in terms of battery chemistries and has similar energy densities at cell level. The energy density of the battery used by Husqvarna is 206,4 Wh/kg whereas in the generic data, it is 180 Wh/kg (Sun, et al., 2020). The input data regarding the battery pack and battery cells is presented in detail in appendix I.

In total, the production phase includes the processing of raw materials at suppliers, processing and assembly at the manufacturing plant along with all the transportations from suppliers to the manufacturing. When a sufficient amount of the products has been produced, they are delivered to Husqvarna's central warehouse (Vogt Duberg, et al., 2020b) in Sweden. The transportation from production to the Swedish market is assigned to the production phase. All the transportations are respectively presented in section 4.2.1.4.

#### *Use*

From the central warehouse in Sweden, the products are then transported to a third party who sell them to customers. The electricity consumption during the usage phase is calculated on the basis of the total number of working hours, which corresponds to:

$$H_{tot}(\text{h}) = 4,36 \times 7 \times 4,5 \text{ h} \times 25 \text{ weeks} \times 8 \text{ years} = 27\,491 \text{ h}$$

In summary, an AM550 work 27 491 hours for a lifespan of 8 years. Presented in table 1, the energy consumption of the AM550 is related to the rated power 0,03 kW and has an efficiency factor of 85 %. This corresponds to:

$$E \text{ (kWh)} = \frac{27\,491 \text{ h} \times 0,03 \text{ kW} \times 1,1}{0,85} = 1067,3 \text{ kWh}$$

In total, 1067,3 kWh is needed if the product is actively used during the cutting season for the whole lifespan of 8 years. During the usage phase, the batteries need to be changed every 2 – 4 years (Tollin, et al., 2019). Hence, the assumption applied in the LCA will be 3 years life expectancy of the battery. The battery will be changed two times during the entire life cycle and the production along with the waste generated from the exchanges is allocated to the use phase. The waste of the last used battery is allocated to the EOL-phase.

Sweden is among the top markets in EU for the AM550 together with France, Germany and Denmark (Tollin, et al., 2019). Since this LCA is limited to the Swedish market, a Swedish electricity grid mix will be used. The environmental profile in GHG emissions per kWh for respective market is presented in table 3.

Table 3. Top four markets within EU and their respective greenhouse gas emission intensity (kg CO<sub>2</sub> emissions per kWh) in 2019. Data collected from EEA (2021).

<i>Market (%)</i>	<i>Greenhouse gas emission intensity (kg CO<sub>2</sub>e/kWh)</i>
<i>Sweden (10%)</i>	0.008
<i>France (28%)</i>	0.052
<i>Germany (22%)</i>	0.338
<i>Denmark (9%)</i>	0.126

#### *End of life*

At the end-of-life of the robotic lawn mower, it is disposed to a waste treatment plant there the electrical waste is disassembled, and the parts are sorted. In regard to the Swedish waste management, inventory data for the incineration and recycling processes were collected mostly as a European average. The amount for each waste type (%) generated from the AM550 is illustrated in figure 5.

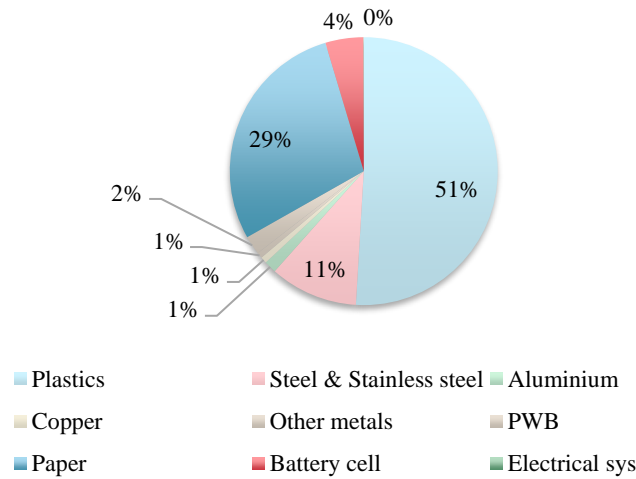


Figure 5. The amount of respective waste (kg) allocated to either end-of-life alternative. Plastic generates the most waste (51%).

Of the plastics used in the AM550, 30% are assumed to be recycled and 70% incinerated in order to reflect the plastic waste management in Sweden (Wallman & Nilsson, 2011). The energy savings from the incineration are calculated to be approximately 374,2 MJ (appendix II, table A3). The dataset used for incineration at an average European municipal waste treatment plant include an estimation of losses during the steam production (average efficiency is approximately 81,9 %) (ELDC).

The circuit boards (PWB/PCB) are shredded, and the precious metals are separated from the rest of the waste to be recycled. The remaining material proceeds to disposal. For the majority of the recycling approaches of PWBs, only approximately 30% of the total weight can be recovered. The rest, roughly 70 %, is not suitable for an efficient recycling process and is sent to either incineration or a landfill (Li, et al., 2004). In this case, the dataset used in the LCA model is “Used printed wiring boards [RoW] treatment of scrap...” (Ecoinvent), which includes the recovery of valuable metals along with the disposal of the residues.

For the metals included in the robotic lawn mower, such as aluminum, copper and steel, are collected as they also have a market value. In the LCA model, the metals are assumed to be 100% recyclable. The allocation principle adapted is that the environmental burden related to the product ends as soon as the material enter the recycling process. Therefore, only the transportation to the recycling plant is added in

the LCA model, but not the electricity or other necessities needed for the recycling process.

Presently, there is a lack of data regarding how many NMC batteries that are recycled. As many other types of lithium-ion batteries usually are grouped together in the same category in the report collection system (Dahllöf, et al. 2019), no specific data for the NMC622 battery could be gathered. However, as for rechargeable lithium-based batteries, the collection rate in Sweden was 14% in 2015 (ProSUM, 2018). The assumption in the LCA is that all of the collected batteries will be recycled. The remaining will be considered EEE-waste and disposed accordingly thereafter (global average).

#### **4.1.2. Scenario 2**

Scenario 2 refers to the remanufactured robotic lawn mower. The production of the original core is included in scenario 2, though described in scenario 1. The life cycle of a used core that intends to be remanufactured is identical to the life cycle explained in scenario 1 with the exception for the end-of-life phase. As illustrated in figure 4, instead of being transported to an EOL-alternative, the used core is transported back to the retailers in order to be remanufactured. Consequently, the life cycle of the remanufactured product is explained in detail below.

##### *Remanufacturing process*

The used core is collected from the customers and transported back to the Swedish retailers. The remanufacturing process at the retailers involves multiple steps: dismantling the product, cleaning the parts, inspect and control the quality, reparation if needed, reassembly and lastly, the testing (figure 6) (Vogt Duberg, et al., 2020b; Parker, et al., 2015).



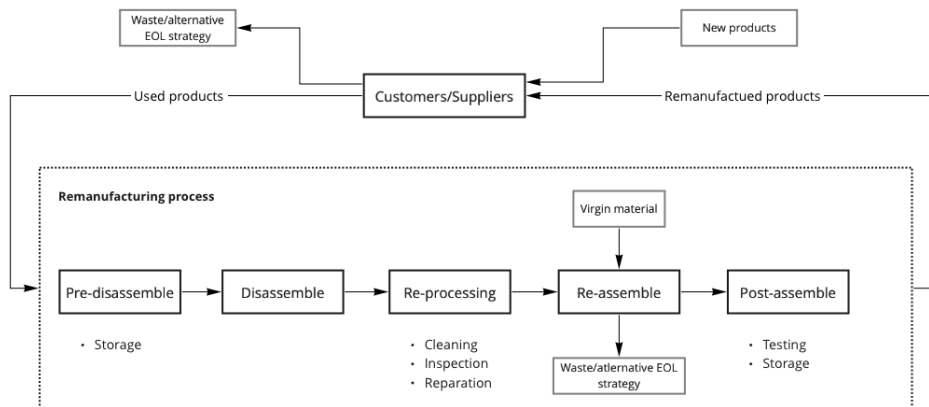


Figure 6. Overview of the remanufacturing system. The remanufacturing process are the phases inside the dotted line (adapted from Vogt Duberg, et al., 2020a and Östlin, 2008). The arrows show the direction of the material flow

The total energy consumption during the remanufacturing process can be allocated to the cleaning process, which need approximately 15 kWh per product<sup>2,3</sup>. The environmental burden from use of other technical equipment, such as rechargeable screwdrivers, is assumed to be insignificant. The assumptions regarding the used equipment and timespan are presented in appendix II, table A4.

There are parts that are standard to be exchanged and others that is changed when necessary. In order to not underestimate the environmental impact of a remanufactured product, the parts that is changed when necessary are to be included in the calculation as well. The parts that are obligatory to change in the remanufacturing process are the knives, air filter, sealing strips, low voltage power supply cable and the battery. If the retailer deems it necessary, the parts to be exchanged as well are the wheel motors, along with the rear and front wheels. Many retailers are planning to exchange the whole wheel system for the front wheel<sup>3,3</sup>. Therefore, to not underestimate the total environmental load, the whole wheel system (front) has been modelled to be exchanged. All components are exchanged one time during the remanufactured products' lifespan, with the exception for the battery. The environmental burden of exchanged batteries after the remanufacturing process are allocated to the usage phase. In the modelled remanufacturing process, only one

<sup>2</sup> Retailer for Husqvarna's automowers, personal communication, 2021-04-07.

battery is included. Further details regarding the parts to be exchanged during the remanufacturing process is presented in appendix II, table A5. The waste generated from the remanufacturing process is the used parts from the exchange. After the post-assembly, the product is sold to the final customer.

#### *Use*

The inputs for the usage phase include the electricity used for charging and the exchange of the battery. During use, the battery will need to be changed three times. The waste from last battery is allocated to the EOL phase. The energy consumption calculation and the lifespan expectancy of the battery in section 2.2.5. is applied on the remanufactured robotic lawn mower as well. If the lifespan of the AM550 is extended from 8 years to 12 years through remanufacturing, it will result in 41 236 working hours and the total amount of energy needed for charging is 1 601 kWh. Since the LCA is limited to the Swedish market, a Swedish electricity grid mix will be used.

#### *End of life*

There is only potential for one remanufacturing process per product<sup>1</sup>. At the end-of-life phase, the RAM550 will be disposed to a waste treatment plant and disassembled the same way as explained in scenario 1, section 3.1.1.3. As there is more plastic in this scenario, the energy savings from the incineration are calculated to be approximately 432 MJ (appendix II, table A3). The amount for each waste type (%) generated from the AM550 is illustrated in figure 7. The extra material is the waste generated from the exchanged parts.

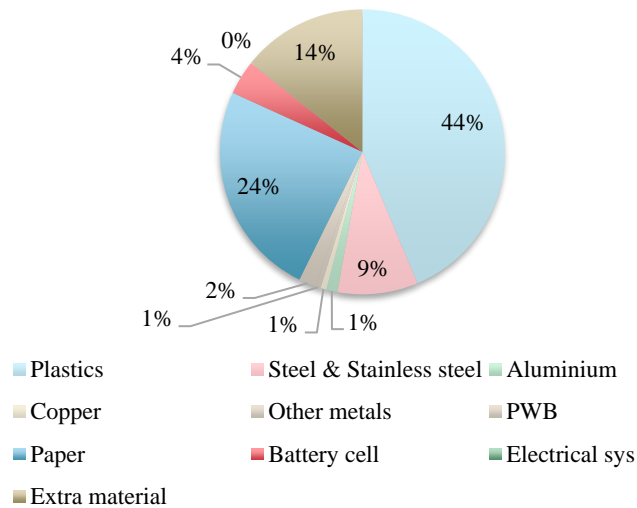


Figure 7. The amount of respective waste (kg) allocated to either end-of-life alternative. Plastic generates the most waste (44%).

#### 4.1.3. Transportation

The estimated distances are based on the location of the suppliers', the manufacturing plant and the Swedish market. In Sweden, Husqvarna's central warehouse is located in Torsvik, Jönköping. From there, AM550 is distributed to retailers. As there are around 300 retailers that handle the products of Husqvarna in Sweden<sup>3</sup>, the assumption regarding the transportations between the warehouse in Torsvik and retailers is that the center of the country is applied as destination. For the transport between retailers and customers, a range of 100 km will be applied. If no data could be gathered for the suppliers' location, the assumption will be that the material/component is transported 500 km with a truck (Tollin, et al., 2019). At disposal of the product, it is either transported back to the retailers or to a waste treatment plant (100 km). The way of transportation is either GLO, RER or RoW averages (table 4).

<sup>3</sup> Johan Vogt Duberg, PhD Student, Environmental Technology and Management (MILJÖ)/ Department of Management and Engineering (IEI), Linköping University, personal communication, 2021-02-25.

Table 4. Generic transportation data. GLO = global, RER = Europe, RoW = Rest-of-the-World.

<i>Vehicle</i>	<i>Process name</i>
<i>Truck</i>	Transport, freight, lorry 16-32 metric ton, euro4 [RER/RoW]
<i>Container ship</i>	Transport, freight, sea, container ship [GLO]
<i>Ferry</i>	Transport, freight, sea, ferry [GLO]

## 4.2. Life Cycle Impact Assessment

In this section, the environmental impacts associated with the life cycles of the two product systems are presented. A comparison between the remanufactured and the manufactured robotic lawn mower was conducted using the impact methods IPCC 2007 GWP 100a and IMPACT 2002+. Sensitivity analyses were conducted in order to analyze the significance of considerable assumptions and limitations which might affect the results of the study. AM550 refers to the manufactured product system (scenario 1) and RAM550 refers to the remanufactured product system (scenario 2).

### 4.2.1. Comparison between AM550 and RAM550 – IPCC 2007 GWP 100a

The environmental impact, illustrated as kg CO<sub>2</sub>-equivalences, for respective scenario is presented in figure 8. The diagram presents the total environmental impact as well as the impact distributed among three phases: production (remanufacturing is included in the production column for the RAM550), usage and EOL. The difference can be interpreted as the environmental benefits that scenario 2 (RAM550) bring by comparison with scenario 1 (AM550), in terms of adapted limitations, assumptions and chosen impact methods.

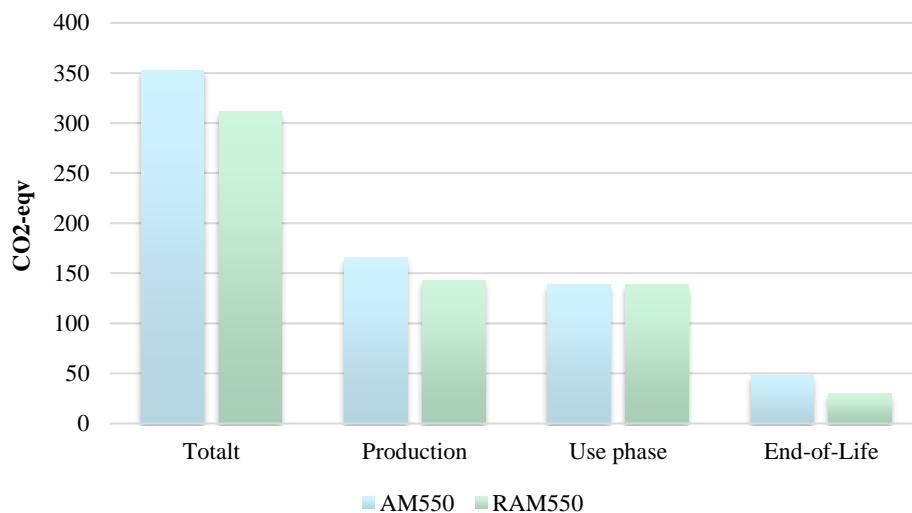


Figure 8. Comparison 1 p 'Life cycle of RAM550' with 1,5 p 'Life cycle of a AM550'; Method IPCC GWP 100a V1.03 / Characterization.

In total, the AM550 contributes to approximately 352 kg CO<sub>2</sub>-equivalences (eqv.) per functional unit while the RAM550 contribute to approximately 311 kg CO<sub>2</sub>-eqv. per functional unit (figure 8). This correlates to a difference of 12%. The production phase is the primary contributor for both scenarios (AM550: 165 kg CO<sub>2</sub>-eqv. / RAM550: 143 kg CO<sub>2</sub>-eqv.). Production of one robotic lawn mower have a contribution of roughly 110 kg CO<sub>2</sub>-eqv. The remanufacturing process contribute to 32 kg CO<sub>2</sub>-eqv whereas a production of half a AM550 contribute to 55 kg CO<sub>2</sub>-eqv. The usage phase is the same, as there is an identical input and output of LCI data. The major contribution of the use phase is related to the use of electricity. There is a slight difference in the EOL-phase, with scenario 2 being the preferable alternative. The contribution distribution between the different life cycle phases for a AM550 is that the production contributes to 47%, the use phase to 39% and the EOL phase to 14%.

#### 4.2.2. Comparison between AM550 and RAM550 – IMPACT 2002+

The IMPACT 2002+ presents the results of a combined midpoint/endpoint approach, which corresponds to linking the LCI results to 15 midpoint categories to four

endpoint categories: human health, ecosystem quality, climate change (as life supporting function) and resources (ILCD Handbook, 2010). How the two product systems perform in respective midpoint impact category is presented in table 4.

Table 4. Characterization results without normalization for scenario 1 and 2 and the difference between them (%). The column A/R shows the preferable option in respective impact category (A=AM550, R=RAM550).

Midpoint categories	Unit*	Life cycle of RAM550	Life cycle of AM550	Difference (%)	A/R
<i>Carcinogens</i>	kg C2H3Cl eq	14.22	18.52	23	R
<i>Non-carcinogens</i>	kg C2H3Cl eq	56.16	70.55	20	R
<i>Respiratory inorganics</i>	kg PM2.5 eq	0.405	0.504	20	R
<i>Ionizing radiation</i>	Bq C-14 eq	6.95E+04	1.03E+05	32	R
<i>Ozone layer depletion</i>	kg CFC-11 eq	4.78E-04	4.83E-04	1	R
<i>Respiratory organics</i>	kg C2H4 eq	0.162	0.212	24	R
<i>Aquatic ecotoxicity</i>	kg TEG water	1.03E+05	1.32E+05	22	R
<i>Terrestrial ecotoxicity</i>	kg TEG soil	3.0E+04	3.72E+04	19	R
<i>Terrestrial acid/eutrophication</i>	kg SO2 eq	6.33	8.03	21	R
<i>Land occupation</i>	m2org.arable	192.6	241.6	20	R
<i>Aquatic acidification</i>	kg SO2 eq	2.04	2.44	16	R
<i>Aquatic eutrophication</i>	kg PO4 P-lim	0.080	0.102	21	R
<i>Global warming</i>	kg CO2 eq	293.1	380.7	23	R
<i>Non-renewable energy</i>	MJ primary	1.34E+04	1.91E+04	29	R
<i>Mineral extraction</i>	MJ surplus	97.0	112.9	14	R

\*Unit descriptions are presented in appendix I.

For all the midpoint impact categories, the remanufactured AM550 performed better compared to the manufactured AM550. The difference for the majority of the impact categories is around 20%. The smallest difference is in *ozone layer depletion* and *mineral extraction*. The greatest difference can be seen in *ionizing radiation* and *non-renewable energy*.

Likewise, in regard to the four endpoint categories the RAM550 contribute to a lesser impact compared to the AM550 (figure 9). The normalized results for the endpoint categories in figure 9 are achieved by dividing the results presented in table 4 with their respective reference values. *Carcinogens*, *non-carcinogens*, *respiratory*

*inorganics, ozone layer depletion, ionizing radiation and respiratory organics* are the impact categories included in *human health*. *Aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/eutrophication and land occupation* are allocated to *ecosystem quality*. *Global warming potential* is the only impact category contributing to *climate change*. Lastly, *resources* include the *mineral extraction* and the *non-renewable energy* (Jolliet, et al., 2003). Considering *human health, ecosystem quality and climate change*, RAM550 achieves a better result by approximately 20%. The remanufactured product system performs 30% better in terms of *resource use*.

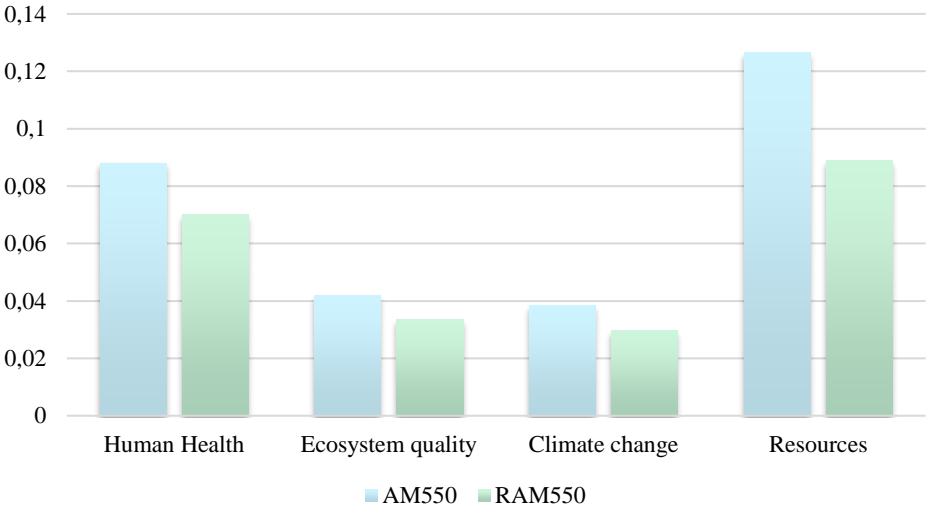


Figure 9. Comparison 1 p 'Life cycle of RAM550' with 1,5 p 'Life cycle of a AM550'; Method IMPACT 2002+/- Normalization.

**4.2.3. Contribution analysis**

The contribution analysis determines which processes that significantly contributes to the environmental burden of the modelled case (Goedkoop, et al 2016). A contribution analysis was performed on the AM550 and its respective material group as presented in table 2. The results illustrated that the bottom chassis is the primary contributor, which can be related to that the wheel motors and the battery exists in this group as they are two of the most contributing systems. Another contribution analysis showed that in the remanufacturing process, the battery, the wheel motors,

rear and front wheels were the most contributing aspects. The graphs illustrating the differences between material groups are presented in appendix III.

#### **4.2.4. Sensitivity analysis**

The sensitivity analysis will evaluate to which extent considerable assumptions are influencing the results (Goedkoop, et al 2016). The analysis will be conducted with the IPCC 2007 GWP 100a method and the results will be presented in CO<sub>2</sub>-equivalences. The chosen variables that may affect the comparative result are:

- Exchanged parts in the remanufacturing process
- Lifespan of a robotic lawn mower
- Number of times the remanufacturing process can occur

As shown in the contribution analysis, the exchange of the wheel motors was, after the battery, the primary contributor in the remanufacturing process. The wheel motors are, together with the front and rear wheels, only changed if necessary. The assumption made in the LCA was to include the parts that is exchanged if necessary, in order to not underestimate a full remanufacturing process. However, as these parts are not always changed on a regular basis, the results of the sensitivity analysis may reflect a more realistic scenario. Therefore, a sensitivity analysis is performed to evaluate the difference in impacts between all of the exchanged parts and of only the mandatory: battery, knives, air filter, sealing strips and the low voltage power supply cable. The results show that only changing the mandatory parts deliver a decrease in GWP by 20 % in the production phase and 14 % in the EOL phase. Setting this in relation to the AM550, the total difference rises from 12 % to 21 % between the AM550 and the RAM550. Consequently, less material achieves a better result in terms of environmental performance as there is less extraction of natural resources and waste generation.

The second variable assumed to be sensitive is the lifespan of a robotic lawn mower. The modelled case assumes that the lifespan of an AM550 is 8 years and for a RAM550, it is 12 years. In order to fulfill the FU of working a total of 41 200 hours, one consumer need either one remanufactured product or one and a half manufactured. Contrary to this, it has been mentioned in internal documents (Tollin,



et al., 2019) that the robotic lawn mower only works approximately 16 000 hours for a total of 8 years. In other words, 42% less than the modelled case. This can amount to a total lifespan of 4 years and in order to fulfill the FU, the consumer will either need three AM550 or one RAM550 plus one new AM550 (if the assumption is that the remanufacturing process can only occur one time per product). The sensitivity analysis results show that the GWP of the AM550 is increased by 56% if the lifespan is shortened by 4 years whereas the GWP of the RAM550 is increased by 43%.

Another assumption that may affect the comparative results between AM550 and RAM550 is the number of times a product can be remanufactured. The aim with remanufacturing is to provide a used product that has the same quality as the previous one (Ijomah & Danis, 2012). In the modelled LCA, the remanufacturing process can extend the lifespan with 4 years, giving a total lifetime of 12 years. If the remanufacturing process can occur more than one time, the assumption will be that a remanufactured product can be used for 16 years. Hence, a sensitivity analysis will investigate the effects of assuming a lifespan of 12 versus 16 years of the remanufactured product. By adding one more remanufacturing process, the impact GWP increases with 9% for the life cycle of a RAM550. Setting this in relation to the AM550 for the same time period will consequently compare two successive life cycles of a new product and the life cycle of one used core that intends to be remanufactured two times. This results in a 36% difference in total GWP with RAM550 being the preferable choice.



## 5. Discussion

This study conducted a comparative LCA for a remanufactured and a manufactured robotic lawn mower produced by Husqvarna. In this section, the obtained results, remanufacture as a business model and the choice of method will be discussed and analyzed. Furthermore, identification of significant issues such as key processes, assumptions and elementary flows are to be highlighted. From the analyzed results, conclusions and recommendations will be presented.

### 5.1. Interpretation

From the results presented in section 4.2, it is evident that remanufacturing of a robotic lawn mower contributes to a lesser environmental burden in terms of chosen impact categories, when compared with its manufactured equivalent. In regard to the total calculated GWP in the IPCC method, remanufacturing can save approximately 12% of carbon emissions related to climate change. The aim with remanufacturing is to reduce the amount of materials used in manufacturing (Guidat, et al., 2017). The presented results in figure 8 illustrate a minor difference in the production phase between the AM550 and RAM550, a 13% difference in kg CO<sub>2</sub>-eqv. This may be because of that the parts to be exchanged, contribute to a great deal of the environmental impact in the product. The contribution analysis of the material groups in the AM550 show that the lower chassis system contributes to the majority of the environmental impact of the whole product (appendix III, table A1). In relation to this, the contribution analysis of the remanufacturing process show that the battery and the wheel motors are the primary contributors in this process (appendix III, table A3). The chassis system includes both the wheel motors as well as the battery. The battery is considered mandatory to be exchanged in the remanufacturing process, but the wheel motors are not. The sensitivity analysis illustrated the influence of assuming

that the parts that is changed when necessary is included, has a considerable impact on the result. By only changing the parts that are mandatory, the difference rise to 21% between the AM550 and the RAM550. This can therefore be seen as a more realistic scenario and the original modelling can be seen as a worst case.

In order to increase the impact coverage, the IMPACT 2002+ method was chosen. For all the 15 midpoint impact categories, the RAM550 was the preferable alternative compared with the AM550, although the difference in respective impact category varied. The majority had a difference around 20%. The smallest difference was in *ozone layer depletion* (1%) and *mineral extraction* (14%), which can be explained with that it is the battery that is the primary contributor in these categories and the number of batteries used in both scenarios are the same. The greatest difference can be seen in *ionizing radiation* (32%) and *non-renewable energy* (29%), which can be linked to the production phase with the material preparation at suppliers. With remanufacturing, this phase in the supply chain is cut off and the use of natural resources and their processing is reduced. This corresponds well with the normalized result in figure 9, the four endpoint categories. The graph illustrates that the aim of remanufacturing, which is material efficiency, is achieved in the category *resources*, resulting in a decrease by approximately 30% (figure 9). Furthermore, RAM550 also decrease the impact on *human health*, *ecosystem quality* and *climate change* by approximately 20%.

### **5.1.1. The influencing parts and processes**

The production phase is the primary contributor in the life cycle of a AM550, contributing to 47%. As mentioned above, it is mainly because of the battery pack and the motors within the chassis system. The use phase contributes to 39% and as illustrated in figure 8, has an environmental impact similar to the production phase. The input in the use phase includes the battery changes and the electricity grid mix. Husqvarna is a global leader in outdoor power products and sells their products in multiple countries. As the use phase contributes to a large part of the total environmental impact, other markets electricity grid mix may influence the results depending on the source of electricity. Presented in table 3 was the four top markets for the AM550 in EU. The market sales in Sweden are 10% and has the lowest kg CO<sub>2</sub> emission/generated kWh (0,008 kg CO<sub>2</sub> e/kWh). France is the top market with

28% and has a GHG emission intensity of 0,052 kg CO<sub>2</sub> e/kWh. This means that the environmental impact related to the charging during use would be significantly bigger. However, regardless of the market the same electricity grid mix is modelled in both scenarios. This does not change to which extent the remanufactured product performs better in terms of environmental performance, compared to a newly manufactured product. The same applies to the battery. There is a limited access to specific data in the battery industry, which prevents proper evaluation of EEE products (Ellingsen, et al., 2013). Therefore, this LCA had to model the battery cell based on secondary data provided by Sun, et al. (2020). The battery pack contributes to a larger part of the lower chassis system and in the use phase. The assumption of what kind of battery cell is used may influence the results to which extent the AM550 aid to its total environmental impact but it will not change the benefits earned from remanufacturing.

### **5.1.2. Interpretation of the sensitivity analysis**

The sensitivity analysis showed that the lifespan of the AM550 can influence the results. By cutting the lifespan of the AM550 in half, the impact doubles as there are a need for more natural resources and waste treatments in comparison with the original model. Even if the lifespan is cut in half, the remanufactured alternative would still be the preferable option.

The sensitivity analysis regarding the number of times the remanufacturing process can occur, presented that the difference in total GWP could increase from 12% to 36% if the process could take place twice. In the current business model, there is only potential for one remanufacturing process<sup>1</sup> and the LCA model was therefore chosen based on this perspective. However, Vogt Duberg<sup>3</sup> assumed that remanufacturing can occur indefinitely with the right approach and access to spare parts. The limiting factor is the advanced technology, an old model may not be valuable enough to remanufacture after 12 years and it depends on the technical development<sup>3</sup>. In regard to a robotic lawn mower, the remanufactured business model would be proven more efficient if the remanufacturing process could be repeated at least two times.

## 5.2. Remanufacture as a business model

The findings of this LCA study are supported by the literature review regarding the environmental benefits with remanufacturing (Guidat, et al., 2017; Peters, 2016; Liu, et al., 2014). However, some of the studied literature in section 2 lacked empirical evidence to support their conclusions whether remanufacturing is a preferable alternative to a linear supply chain. An identified issue with implementation of remanufacturing for OEMs is the collection of used cores and where to establish the location for the process as to which extent the benefits from remanufacturing are, is exceedingly related to the context of study and its location (Lindahl, et al. 2006). Due to an unsuitable location for the remanufacturing process, the implementation may result in excessive emissions from increased number of transports required to return the used cores (Lindahl, et al. 2006). The remanufacture process may also inquire more energy use depending on the products, changing the overall acknowledgement that remanufacture is the preferable alternative. Therefore, it is recommended to perform case studies in order to better understand how changes in manufacturing strategies can be cost-effective and environmentally efficient (Kurilova-Palisaitiene, et al., 2020).

Another recognized issue is that there is a knowledge gap and uncertainty regarding remanufactured products among Swedish customers, which may result in low market demand (Kabel, et al. 2020; Kurilova-Palisaitiene, et al., 2020). This might be one of the reasons remanufacturing is not as widespread as it could have been among OEMs, considering the potential environmental and economic benefits. No cost analysis was performed in this study hence, no conclusion could be made regarding the economic profits. However, Vogt Duberg, et al. (2021) concluded that the case company may be profitable implementing a remanufacturing process following certain conditions. Furthermore, this LCA study shows that the case company can benefit from implementing a remanufacture process from an environmental point of view as well. Their current business model in this case is a linear product system and their design of AM550 is aimed for a short lifecycle. This is not preferable for remanufacture as a business model. Increased benefits can be achieved if the product and the supply chain is designed for remanufacturing from the beginning, when the production system is in line and logistics supports exist. In addition to this, the case company should market that the remanufactured product will have the same product quality as

a newly manufactured, in order to influence the attitude towards remanufactured products towards the better and create customer demand in the Swedish market.

### 5.3. Method discussion

An instrumental case study was chosen as a method in order to comply with the aim of the study: to evaluate as well as compare the environmental effects of linear and circular production systems in hardware manufacturing sectors, focusing on EEE products. Although an instrumental case study has its advantages by being able to generalize the result in order to be representative for other products rather than only the specific chosen case, a common criticism is that a general case study method provide an insufficient basis for generalization (Yin, 2014). Since a small number of subjects are used or in this case, the dependency of one single case study, it can cause difficulties to reach a generalizing conclusion. Contrary to this, Yin (2014) claims that the aim of case studies is to expand and generalize theories rather than to deduce probabilities. In this sense, the generalization of the case study's results will be more of an analytical generalization compared to a statistical one.

The challenge of conducting an LCA study is to develop a model with as few subjective modelling decisions as possible. In order to handle data intensities and other complexities in the model, simplifications are made (Goedkoop et al., 2016). A product that intends to be remanufactured can be assessed whether, and to what extent, it is an advantageous option in regard to the environment compared to a manufactured one, using an LCA. In the background (section 2) presented several studies that a remanufactured product is the more environmentally friendly option but that it is related to the context of the study. Depending on the methodological choices for which kind of approach is chosen, different perspectives will lead to different system boundaries and allocation, which in turn leads to a different LCI and therefore to different results. This applies to both within product groups and between different kinds of products. An example of how various approaches for the same product can influence the results can be shown by Biswas et al. (2013) and Zanghelini et al. (2014). Both articles conducted a comparative LCA for a remanufactured and a manufactured air compressor. In Biswas et al. (2013), the environmental load of the original air compressor is excluded in the system boundary, focusing only on the remanufactured

product. The result presented is that a remanufactured air compressor contributes to a 96 % reduction in carbon emissions compared to their manufactured counterpart. In Zanghelini et al. (2014) the original air compressor is taken into account of the total environmental load. This generated a result of 46 % reduction in carbon emission for a remanufactured product compared to a manufactured one. This example illustrates that the findings of a comparative LCA of remanufacturing and manufacturing can be contextual, and compared to the results of this thesis, illustrate that there is a difference between different kind of product groups.

The question to be asked when conducting an LCA for a remanufactured product is which of the two methods are the correct approach? As there are no specific guidelines or standards for remanufactured products, one that intends to perform an LCA on remanufactured products will have to rely on the general guidelines and other scientific literature (Ekvall, et al., 2020; Peters, 2016). When it comes to choosing relevant and suitable impact categories and indicators in an LCA model, the focus should be based on the goal of the study and its application along with an appropriate impact coverage (Benedetto & Klemeš, 2015). It is therefore of importance to use standardized metrics and identify environmental assessment indicators that is not too broad or generic (Goedkoop et al., 2016; Benedetto & Klemeš, 2015). For robotic lawn mowers, with divided attention from the case company as well for academic purposes, a greater focus was applied on GHG emissions along with other relevant impact categories to support the conclusion that the remanufactured product is, in terms of environmental performance, the preferable alternative.

### 5.3. Further research

Further research regarding this subject could be to alter the assumptions in the LCA model. For instance, it could be of interest to investigate the different types of electricity grid mixes for the markets of the AM550 or follow the alternative business model as propose in Vogt Duberg, et al. (2020b). Especially if the business model includes switching the remanufacturing process to another market. To test the results from an economic perspective other tools could be applied, such as the lifecycle costing



(LCC) approach. Another investigation that would be of interest is to test the theory of the remanufacturing process occurring twice in practice. If it is feasible, the aim would be to achieve a product design that withstand to be remanufactured twice with the same satisfactory results as the original.

## 6. Conclusions

The following conclusions are based on the findings of the study:

- In conclusion, the remanufacturing of a robotic lawn mower contributes to a lesser environmental burden in terms of all chosen impact categories, when compared with its manufactured equivalent.
- The material group that is influencing the environmental performance the most is the lower chassis system, primarily because of the battery and the motors.
- The production phase contributed to the majority of the total environmental impact, followed by the use phase and lastly the end-of-life phase.
- Assumptions regarding the lifespan of the AM550, number of times a product can be remanufactured and type of exchanged parts in the remanufacturing process are considered sensitive variables as they influence the results.
- The benefits with implementing a remanufacturing process for OEMs are contingent to environmental benefits, market demand and regulatory actions of policy makers.
- An identified issue with implementation of remanufacturing for OEMs is the collection of used cores and where to establish the location for the process as to which extent the benefits from remanufacturing are, is exceedingly related to the context of study and its location.

Further research and recommendations:

- Future studies could be to conduct an LCA-study for different markets and business models as well as a lifecycle costing analysis.
- Perform testing of the theory that the remanufacturing process of a robotic lawn mower can occur at least twice with satisfactory results.



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# Appendix

Following appendix I, describes the units for the impact categories included in the IMPACT 2002+ method. Appendix II, which introduces certain data descriptions and tables regarding the input of data in the LCA model. As information about Husqvarna's robotic lawn mower is considered proprietary technological data, no detailed data description is presented in the thesis. Appendix III presents the graphs for the contribution analysis. Appendix IV presents a list of relevant stakeholders that were interviewed.

## Appendix I. Unit description.

The table below explain the respective units for the midpoint categories following the IMPACT 2002+ method (Joliet, et al., 2003).

Table A1. Unit descriptions.

<i>Midpoint categories</i>	<i>Unit</i>	<i>Description</i>
<i>Carcinogens</i>	kg C2H3Cl eq	kg chloroethylene into air
<i>Non-carcinogens</i>	kg C2H3Cl eq	kg chloroethylene into air
<i>Respiratory inorganics</i>	kg PM2.5 eq	kg PM2.5 into air
<i>Ionizing radiation</i>	Bq C-14 eq	Bq carbon-14 into air
<i>Ozone layer depletion</i>	kg CFC-11 eq	kg CFC-11 into air
<i>Respiratory organics</i>	kg C2H4 eq	kg ethylene into air
<i>Aquatic ecotoxicity</i>	kg TEG water	kg triethylene glycol into water
<i>Terrestrial ecotoxicity</i>	kg TEG soil	kg triethylene glycol into water
<i>Terrestrial acid/eutrophication</i>	kg SO2 eq	kg sulphur dioxide into air

<i>Land occupation</i>	m <sup>2</sup> org.arable	m <sup>2</sup> organic arable land
<i>Aquatic acidification</i>	kg SO <sub>2</sub> eq	kg sulphur dioxide into air
<i>Aquatic eutrophication</i>	kg PO <sub>4</sub> P-lim	kg phosphate into water
<i>Global warming</i>	kg CO <sub>2</sub> eq	kg carbon dioxide into air
<i>Non-renewable energy</i>	MJ primary	MJ total primary non-renewable energy
<i>Mineral extraction</i>	MJ surplus	MJ additional energy needed for extraction

## Appendix II. Data description and tables.

The electricity used in the production phase is wind power from Örsted (Denmark) (Tollin, et al., 2019). The waste generated from this part of the supply chain is plastic waste of 400 g, divided into 18 g PP, 20 g ABS, 26 g nylon, 233 g mixed plastic and 103 g plastic purging (Tollin, et al., 2019).

The battery pack included in the AM550 is BMZ 5S2P Type 14 and is produced along with assembled in Germany. The battery cells are produced and shipped from Malaysia (Tollin, et al., 2019). The total weight of one battery pack is 736,2 g and is included in the bottom chassis (table 2). Two battery packs are installed in the AM550. Specific product data regarding the battery cells were deemed proprietary technological data and considered sensitive information by the provider. Therefore, a substitution was chosen from literature (Sun, et al., 2010). The chosen battery cell is a NMC622, used in a passenger BEV and has a cell weight of 576 kg. Consequently, an electric vehicle battery is much larger than the ones used in a robotic lawn mower (2x450g), in fact, approximately 640 times bigger. The two battery types are similar in terms of battery chemistries. The assumption is therefore that that the materials presented in the study by Sun, et al. (2020) is the same for the battery cell used by Husqvarna, but the amount is 640 times less than presented in the literature. The input data is gathered from the supplementary material of Sun, et al. (2020).

In the table below is the calculation of the energy savings from the incineration of plastic at a Swedish waste treatment plant (table A3).

Table A3. The energy savings from the incineration (70% of the total weight) are calculated based on the calorific value used by Wallman & Nilsson (2011) and the summarized weight at the EOL phase for respective scenario.

Parameter	AM550	RAM550
Calorific value (MJ/kg)	40	40
Weight (kg)	9.356	11.327
Energy (MJ)	374.24	453.08

Table A4 shows the total energy consumption in the remanufacturing process.

Table A4. Assumptions regarding the equipment and time during the remanufacturing process, based on interview with a retailer<sup>2</sup>.

Equipment	Energy (kW)	Time (h)	Energy consumption (kWh)	Comment
Air compressor	4	0.25	1	Air compressor used to remove the first layer of dirt and grass and later used to dry the product.
Washing machine	12.6	0.133	13.44	The retailer can either wash by hand or by using a washing machine. The assumption in this scenario is that the retailer uses a washing machine.
Pressure washer	3.3	0.167	0.55	Pressure washer with hot water used on the wheels.

The input data in the LCA model for the parts exchanged in the remanufacturing process are presented in table A5. The different parts are divided based on whether they are mandatory exchanged or changed when necessary.

Table A5. Materials/parts to be exchanged during the remanufacturing process and their respective weights and processes. GLO = global, RER = Europe, RoW = Rest-of-the-World, RAS = Region of Asia.

Exchanged part	Material	Weight (g)	Process name
Always			
<b>Cutting system</b>			

<b>Knives</b>	Steel	8.1	Metal working, average for steel product manufacturing [RER]
<b>Cutting disc</b>	ABS-PC	114	Injection moulding [RER] processing, APOS, U
<b>Air filter</b>	Non-woven polyester	0.15	Textile, non-woven polyexter [GLO] market for textile, non-woven polyexter APOS, U
<b>Sealing strips</b>	EPDM	40	Synthetic rubber [RER] production
	NBR	0.6	Injection moulding [RER] processing, APOS, U
	Steel	0.4	Metal working, average for steel product manufacturing [RER]
<b>Battery</b>	Li-ion battery	900	See supplementary material by Sun, et al., 2020.
	PWB	40	Printed wiring board, through-hole mounted, unspecified, Pb free [GLO] production APOS, U
	Steel	14.8	Steel wire rod/EU
	ABS-PC	506	Injection moulding [RER] processing, APOS, U
	Polypropylene	11.6	Polypropylene injection moulding part (PP)[RER]
<b>Low voltage cable</b>	Polyvinylchloride	0.32	Injection moulding [RoW] processing APOS, U
	Tin	0.15	Tin [RoW] production APOS, U
	Polyamide	8.4	Nylon 6 [RoW] production APOS, U
	Cable	5.42	Cable, unspecified [GLO]
<i>When necessary</i>			
<b>Wheels</b>			
<b>Rear wheel</b>	Polyamide	466	Nylon 6, glass-filled [RER] production APOS, U
	Polyurethane	266	Injection moulding [RoW] processing APOS, U
<b>Whole front wheel*</b>	EPDM	110.8	Synthetic rubber [RoW] production APOS, U
	Polypropylene	186.6	Injection moulding [RoW] processing APOS, U
	NBR		
	Stainless steel	25.16	Metal working, average for chromium steel product manufacturing [RER]
	Steel	1.16	Metal working, average for steel product manufacturing [RER]
<b>Wheel motors</b>	Aluminium	54	Metal working, average for aluminium product manufacturing [RER]
	Neodymium	80	Neodymium oxide [GLO] market for APOS, U
	Steel	888	Metal working, average for steel product manufacturing [RER]

Copper	68	Copper [RAS] production, primary APOS, U
Polypropylene	708	Injection moulding E
POM	110	Injection moulding [RoW] processing APOS, U
EPDM	1	Synthetic rubber [RER] production APOS, U

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*\*Many retailers are planning to exchange the whole wheel system for the front wheel<sup>3</sup>. Therefore, to not underestimate the total environmental load, the whole wheel system (front) has been modelled to be exchanged.*



### Appendix III. Contribution analysis

A contribution analysis was performed on the AM550 and its respective material group as presented in table 2 plus the documentation and packaging systems (figure AT). The LCIA method IMPACT 2002+ was used.

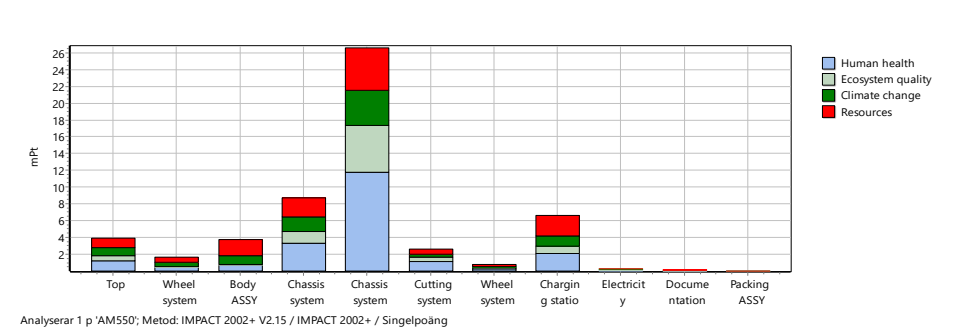


Figure A1. Contribution analysis of the whole AM550.

Another contribution analysis was conducted for the RAM550 and the remanufacturing process.

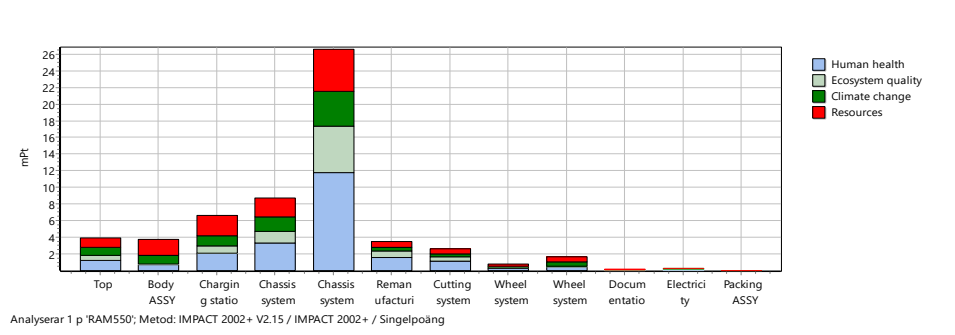


Figure A2. Contribution analysis of the whole AM550 plus the remanufacturing process.

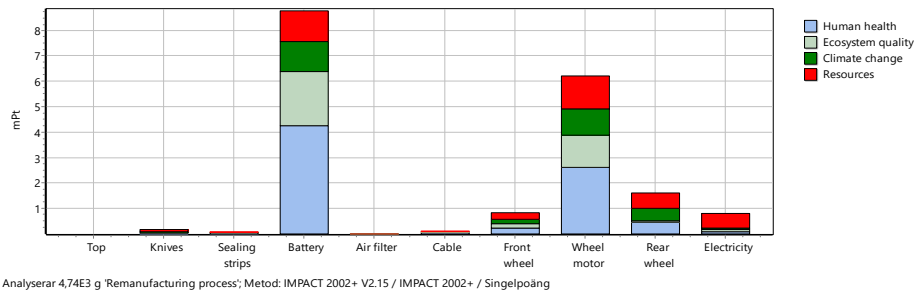


Figure A3. Contribution analysis of the remanufacturing process, the material groups that are exchanged.

## Appendix IV. Interviews with relevant stakeholders

Semi-structured interviews were conducted with people who represent the case company/industry as well as experts in methodological issues of LCA and remanufacturing. The objective was to complement literature with relevant product and business specific information, including data relevant for the LCA study. The interviews were designed to collect well-developed answers along with the possibility to ask follow-up questions. In addition, the flexibility of semi-structured interviews made it possible to verify and discuss assumptions as well as limitations made in the LCA model. Even though meeting with the relevant stakeholders in person would have added value to the interview, the interviews were conducted over online or via mail because of the ongoing pandemic.

Table A6. List of relevant stakeholders that contributed with information and data to the study.

Organization	Position	Type of communication	Date	Relevance for the thesis
Husqvarna	Vice President of Sustainability Affairs	Zoom meeting	2021-04-01	Informant for the case study. Specific product data was received.

<i>Ramboll</i>	Senior Consultant	Zoom meeting	2021-03-21	LCA-expert.
<i>Linköping University</i>	PhD Student	Zoom meeting	2021-02-25	Informant of the remanufacturing process for a robotic lawn mower.
<i>Robo10</i>	Retailer	Zoom meeting	2021-04-07	Informant of the remanufacturing process for a robotic lawn mower.
<i>IVL Swedish Environmental Research Institute Centre for Environmental and Climate Science (CEC).</i>	Team Leader Life Cycle Management	Mail conversation	2021-04-08	LCA-expert.
	Researcher	Zoom meeting	2021-03-16	LCA-expert.



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