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Evaluation of circular economy potential in the life cycle of low voltage marine motors

A case study of identifying environmental hotspots and new business models

Master's thesis in Production Engineering Master Program

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Master's thesis X 2020:XXX

Department of Industrial and Material Science
Division of Production Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

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Chalmers digitaltryck Gothenburg, Sweden 2020

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Abstract

Today's society is more enlightened about the earth's resources and how we, the humans, are exceeding the usage of those. This problem is something that affects all manufacturing companies in one way or another, e.g. by increased customer demands on environmental friendly products and stricter environmental requirements from the governments. A work approach that, when done properly, is highly protective towards the environment is circular economy. Circular economy is an approach that prolongs the usage of products and resources by circling them back into the system. This master's thesis is based on a circular economy initiative at ABB Corporate Research in Västerås. The aim of this project is divided into two parts; perform a screening life cycle assessment (LCA) of one of ABB's low voltage marine motors in order to find CO_2 peaks and suggest changes to minimize those. The second aim is to evaluate whether the motors can be provided to the customers in a more circular way.

The result of the LCA performed in this study shows that the use-phase of the low voltage marine motors have, by far, the highest environmental impact in terms of global warming potential (GWP). The use-phase stands for around 99% of the total GWP of the motors. The use-phase however is something that ABB have little to no possibility to affect. The phase in the motors life cycle that had the second highest impact on the GWP is the material acquisition which is a part that ABB have high possibilities to affect.

The result of evaluating new, more circular, business models shows that there is a chance to provide the customers with motors in a more circular matter. Two circular economy business models (CEBM) was developed and evaluated in the study. The two CEBM are; the remanufacturing/refurbishment model where the motors and its components are to be repaired and reused to the longest extent and when the components are used until they can no longer be repaired they are to be properly recycled. The second model is the product service system (PSS) model where the motors no longer will be sold in a conventional way. Instead the function of the motors will be sold e.g. mechanical motion per-minute.

The two parts of the study were linked together and it was shown in the study that, by adapting to the remanufacturing model there is a chance of reducing the GWP in all phases except the use-phase with 40% due to decreased need of virgin material. By adapting to the PSS model it was proved that there was a possibility to reduce the GWP in the material acquisition-phase, the manufacturing-phase and the end-of-life-phase with 75%. Furthermore, the work procedure in this report could be used as guideline for companies and students for similar projects. However, be aware that adoptions would most likely be needed which can be read throughout the report.

Keywords: Circular economy, life cycle assessment, evaluation of circular business models, low voltage marine motors.

Acknowledgement

The following master's thesis was carried out as a final project in the master programme production engineering at Chalmers University of Technology in Gothenburg, Sweden. The thesis was conducted in collaboration with ABB Corporate Research in Västerås during the spring of 2020.

To begin with, we want to thank everyone who has in any way contributed to the completion of this thesis. Then, we want to direct a special thank you to Mikael Dahlgren at Corporate Research, ABB, who made it possible to perform this project in the first place. We would then want to thank our supervisor at ABB, Santanu Singha, for all the help and support throughout the project. Furthermore, we want to thank Erik Johansson at ABB who have been with us throughout the project, almost as an extra supervisor, for all the insight and idea bouncing. We would then like to mention and thank the following employees at ABB for being a part of the project in interviews and for showing interest in our work, Göran Paulsson, Sjoerd Bosga, Peter Isberg och Fredrik Sahlén.

From Chalmers side we want to direct gratitudes to our tutor, Xiaoxia Chen, who has been a great support and a person who has provided us with great insight and fruitful discussions, the thesis would not have been what it is today without her. Furthermore, we want to thank Mélanie Despeisse, our examiner, who truly is an expert when it comes to these kinds of projects. Her thoughts and inputs on the project and the presentation have been very valuable to us.

Lastly, a project of this size is highly demanding regarding time and effort. We therefore want to thank our spouses, family and friends who have been supporting us throughout this time.

Henrik Friman

Gothenburg, May 2020

Gustav Burman

Gothenburg, May 2020

Glossary

Abbreviations

BM	Business model
CEBM	Circular economy business model
EoL	End-of-life
FU	Functional unit
GWP	Global warming potential
IE	International efficiency
KPI	Key performance indicator
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LV	Low voltage
PSS	Product service system
SWOT	Strengths weaknesses opportunities threats

Definitions

Triple bottom line	Sustainability is a term that consists of three parts, environmental, social and economical.
Blue collar workers	Manual labor worker, e.g. assemblers and machine operators.
White collar workers	Non manual labourers e.g. clerks.
Business model 1	One of the proposed new business models for ABB's LV motors, based on a remanufacturing/refurbishment model.
Business model 2	One of the proposed new business models for ABB's LV motors, based on a PSS model.

Table of content

1. Introduction

The following chapter presents an introduction to the study. It consists of the background to the project, the purpose and target of the study, the research questions that the project aims to answer and lastly the delimitations of the project.

1.1 Background

Today's enlightened society is well aware that we are spending more of the natural resources than is available. By implementing a more circular approach the transformation to a sustainable society could be achieved. Circular economy is an approach that aims to prolong the usage of resources and products and therefore reduce the need of raw material (Ellen MacArthur foundation, 2017b).

Old low voltage (LV) motors are expensive and sometimes impossible to rebuild in order to make them energy efficient and are therefore not supposed to be reused. Furthermore, the old motors are often inefficient and wrongly dimensioned for their applications which leads to huge losses in energy (ABB, 2019). The best way to handle the old motors are instead to assure that the materials within the motors does not end up in landfill but rather gets recycled and reused. The use of recycled material is a vital part for production companies in their work towards a carbon dioxide neutral production. Another vital part for companies in the industry sector to reach their environmental targets is to use rightly dimensioned and energy efficient motors. Circular economy has a great potential in for instance, freeing up electric capacity within the industry and production sector (ABB, 2019).

The shipping industry are facing stricter regulations regarding environmental impacts and emissions and the International Marine Organization (IMO) has currently suggested limits and regulations for ships within Emission Controlled Areas (International Marine Organization, 2018). Hence, there is a high potential in the market of LV motors in the marine sector for improvements.

This thesis work has evolved from a circular initiative project at ABB Corporate Research in Västerås. The project are performed to evaluate the environmental impact the motors have during their lifetime. Furthermore, the project aims to evaluate whether the motors could be provided to the customers in a more circular way.

ABB's LV marine motors are used in applications such as pumps in engine rooms, steering pumps, cargo pumps, winches, compressors, ventilation, thrusters and hydraulic power packs (ABB, 2016). What is especially important and specific for marine motors is that the motors are more resistant to corrosion due to the marine environment.

1.2 Purpose

The thesis work is divided into two main parts, the first part is environmental hotspot detection through life cycle assessment (LCA) and possible solutions for minimizing these. The second part is evaluation of circular business models and analysis of current strategies used by other companies regarding circular economy.

The goal of the first part is to identify the environmental footprint at each step of the product life cycle of LV marine motors and highlight the hotspots. The steps in the product life cycle that are to be evaluated are bill of materials, material acquisition, manufacturing methods, transports, usage and today's end-of-life scenario. After identifying the hotspots in the process, suggestions are to be proposed on what could be done to decrease the CO_2 footprint.

The goal for the other part of the thesis project is to evaluate how to do business with LV motors for marine use in a circular way. The work for providing ABB with possible business models include analysis of other companies that successfully have adapted to circular economy, SWOT-analysis and morphological evaluations. It is important during this work to have all the sustainability aspects in mind, i.e. the triple bottom line. The business models must be profitable environmentally, socially and economically since ABB is a commercial company.

1.3 Research questions

Based on the purpose and target two different research questions are formed. These questions will be answered throughout the research.

> *RQ1: What are the CO_2 hotspots along ABB's LV marine motors life cycle? How to reduce the environmental impact of these hotspots?*

This research question aims to find hotspots in the current life cycle of ABB´s LV motors. The stages that will be investigated to find potential CO_2 hotspots are manufacturing, usage, transportation and end-of-life. Further, the purpose of this research question is to investigate and evaluate possible changes and improvements to reduce the impact of the CO_2 hotspots. That in turn means to come up with recommendations and possible changes for the steps in the lifetime of the motor.

> *RQ2: Which business models have potentials for ABB in order to enable the providing of LV marine motors in a more circular way and thereby reduce the environmental impact?*

The purpose of RQ2 is to evaluate different circular business models and investigate if these can be advantageous for ABB and therefore change the way they provide and distributes their LV marine motors. Furthermore, the business models are to be assessed regarding their environmental impact compared to the current case.

1.4 Delimitations

In this project, the scope will be limited to only one motor and one application due to the time frame and to be able to focus on the business model to a greater extent. This will exclude similar motors used in other applications that previously was a part of the project, i.e. food & beverage, mining and traction.

Further, it is predetermined for this project (by the project management) that the LCA is performed only to collect and analyze data for the CO_2 emissions. Because of this, the Life cycle impact assessment (LCIA) is delimited to investigate the impact category climate change with the impact factor of GWP.

Because of the current global state with the Covid-19 outbreak, information about the manufacturing part of the LCA has been limited. Both interviews with important stakeholders, such as the recycling company, and visits at the production site in Vaasa have not been possible to do which have limited the data gathering. The lack of data in the motor assembly-phase forced the LCA to be conducted without that part. The virus outbreak furthermore resulted in making the LCA of the project a lower priority.

2. Theoretical framework

This chapter brings up the theoretical framework that lays as a foundation for being able to fully comprehend the study. The chapter consists of theory regarding life cycle assessment, circular economy and circular business models.

2.1 Life cycle assessment

Life cycle assessment (LCA) is a method to map the material, energy and emission flows in a product's life cycle (Baumann and Tillman, 2004). The method is used for analyzing environmental aspects and impacts in product systems and is defined so in the international standard ISO 14040 and 14044 (Klöpffer and Grahl, 2014; ISO 14040, 2006; ISO 14044, 2006). LCA is an iterative method which means that as the assessment develops over time new facts and insight will be gathered and these can have an impact on how the LCA is performed. According to the ISO-standardization two different approaches to LCA have been developed over the years. The first approach is the elementary flows and potential environmental impacts that a specific product system has over its lifetime. The second approach is to study the environmental impacts of potential future changes between different product systems (ISO 14040, 2006).

There are different depths of LCA, one is the screening LCA which is suitable for internal communication within a company. The screening LCA can be a good method to backup decisions regarding a certain evaluated product. It can further be used to identify hotspots in the product system, find relevant activities and potential improvement possibilities (Klöpffer & Grahl, 2014; PRé, 2018; Gantner, 2012). The screening LCA is a smaller and quicker version of the full ISO-compliant LCA (PRé, 2018). LCA have various applications, it can assist in decision makings regarding basis for purchases, product design and product development. LCA can further be used in learning and exploring purposes such as choice of key performance indicators (KPI's), perceive more knowledge about a product system and finding improvement potential within it. Lastly, LCA can be used for communication purposes such as environmental declarations and benchmarking (Baumann and Tillman, 2004). For the later, environmental declarations and benchmarking, a full ISO-compliant LCA must be done accordingly to the ISO standard 14040/44 in order for it to be valid. The LCA method consists of four steps which are shown in figure 1.

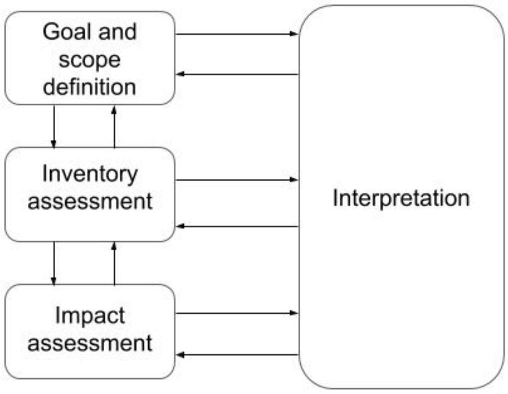

Figure 1. The four steps in the LCA method (adapted from ISO 14040, 2006, p.8).

Goal and scope definition

The first step in performing LCA is to define the goals and the scope of the study (Baumann and Tillman, 2004; Klöpffer and Grahl, 2014; ISO 14040, 2006). It is important to remember that the method is iterative, which means that the goals and scope are to constantly be reevaluated through the study as new facts and insights that surfaces can lead to rewritings of the goals, system boundaries etc. The goals of the life cycle assessment must however be defined in the beginning of the process. The following questions, presented in ISO 14040 (2006), are to be answered;

What is the intended application of the study?
What is the reason for conducting the LCA?
To whom is the result intended to be communicated towards?
How are the results intended to be used, publicly or internally?

How the questions above are answered determines how the LCA is performed. For instance, if the results are to be publicly presented it would set higher demands on the trustworthiness of LCA and in order to achieve that, highly qualitative data must be used in the study (Klöpffer and Grahl, 2014). Gathering good data is time consuming and therefore an LCA that is to be used for public reasons require more resources than for instance a screening LCA that is to be used internally as an indicator for potential improvement hotspots (Klöpffer and Grahl, 2014).

When the goals of the study have been established the scope of the LCA is to be determined. The scope must be defined in a way that makes it compatible and sufficient enough to meet the stated goals (ISO 14040). The scope should contain the following parts.

Product system

The product system is the first item that must be defined in the scope of the LCA (Klöpffer & Grahl, 2014; ISO 14040, 2006). The product system is to include all functions of the system and these are the basis for the functional unit (FU), which is thoroughly described in the paragraph "functional unit". The product system is often represented in a flow chart where the system boundary is clearly visible. In the early state of the LCA the definition of the system should be brief but as precise as possible (Klöpffer and Grahl, 2014). An example of a simplified flow chart of the product system can be seen in figure 2.

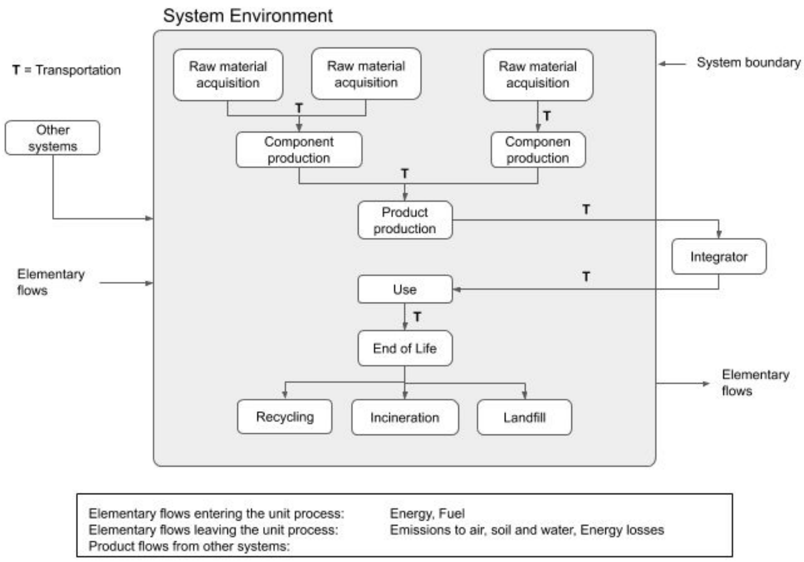

Figure 2. An example on how a product system can be represented in a flow chart (adapted from ISO 14040, 2006, p.10).

The functions in the flow chart are represented as steps that are called unit processes. The unit processes make up the product system and they are linked together with intermediate flows. The input flows and output flows related to each unit process are elementary flows and/or products (ISO 14040, 2006). A graphic representation of the unit processes can be seen in figure 3.

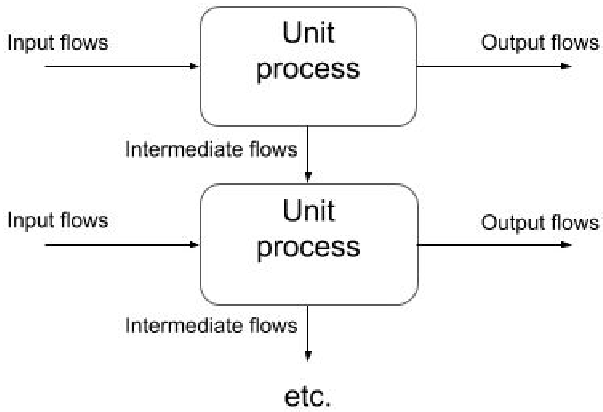

Figure 3. A representation of how the unit processes are linked together which ultimately make up for the entire product system (adapted from ISO 14040, 2006, p.10).

System boundary
LCA of a product system is a model of the physical system where the key elements are described. The system boundaries enclose the unit processes that are to be used in the study and they will be what is included in the model of the system. In the base case, inputs and outputs of the system are elementary flows (ISO 14040, 2006). That is not always the case and therefore flows that have no specific influence on the conclusion of the study should not be analyzed and use up resources for the LCA (ISO 14040, 2006).

What determines the system boundaries of the model are the goal and scope, the intended application, the audience to whom it is presented to, assumptions, cost- and data constraints and the cut-off criteria (ISO 14040, 2006). The criteria that sets the boundaries are important for the credibility and the possibility to reach the goals of the LCA study (ISO 14040, 2006).

Functional unit
The functional unit defines the performance characteristics of the product that are to be studied in the life cycle assessment. The product that is to be studied may have several functions and therefore, the functional unit that is selected is based upon the goals and scope of the LCA. The functional unit is important in order to have a reference to which the inputs and the outputs of the system are related to. This is needed to be able to make fair comparisons between LCA results of different systems (ISO 14040, 2006).

Life cycle inventory analysis
The life cycle inventory analysis (LCI) is the part of the LCA where data is collected and calculated in order to quantify inputs and outputs in the product system (ISO 14044, 2006). The LCI is a linear system analysis where material and energy are evaluated in an iterative way (Klöpffer and Grahl, 2014). The way the analysis is iterative is when data is collected, new insights are gained about the system and therefore new requirements and limitations can be identified. That in turn could require changes in order to reach the goals and scope of the LCA, e.g. other data collection methods. In some cases, the new insights gathered in the LCI identifies issues large enough to require rewriting of the overall goals and scopes of the study (ISO 14044, 2006). The LCI is performed in the following steps, which are described in the subsequent paragraphs; Data collection, Calculation of data and Allocation.

Data collection
The first step in the LCI-analysis is to collect data for all the unit processes that have been defined within the system boundaries. Data that is collected from open sources must be referenced and the date when it is acquisitioned must be documented. It must be stated if significant data is used that does not match the correct quality (ISO 14040, 2006). The process of collecting data is highly resource demanding and it should be stated in the scope and documented in the report about the practical restraints that are made regarding the data collection. The data collected for the LCI can be grouped under major headings such as; energy flows, raw material flows, products, bi-products, waste, emissions to air, emissions to soil, emissions to water and other environmental aspects (ISO 14044, 2006).

Data calculations
When data is collected, procedures for calculations must be established and they are to be well documented, for instance when assumptions are made (ISO 14040, 2006). The procedures are to generate inventory results regarding the defined product system, each unit

processes and for the functional unit in the system that is modeled. The calculations are further made to validate the collected data, relate data to the unit processes and to relate the data to the functional unit´s reference flow (ISO 14044, 2006). Calculations of the energy flow should take into account the energy mix used in the product system. For instance, it should be documented how much fossil fuels, biofuels, nuclear power and renewable energy that is used to retrieve electricity and with what efficiency. That could then be recalculated to energy flow or other elementary flows (ISO 14040, 2006).

Allocations
Most industry procedures generate more than one flow and very few builds on a strictly linear ratio between inputs and outputs (ISO 14044, 2006). Therefore, allocations are often to be made. If allocations must be made, they are to be clearly stated in the study but if it is possible they are to be avoided as much as possible. Avoiding allocations could be made by dividing the unit processes into two or more sub-processes where the related inputs and outputs are collected (ISO 14040, 2006).

Life cycle impact assessment
The final step in the LCA is the life cycle impact assessment (LCIA) which is the phase where the result of the life cycle inventory (LCI) is used to identify potential environmental impacts caused by the product system. The LCIA phase connects the LCI results to specific environmental impact categories and category indicators which makes the impacts understandable. Furthermore, the LCIA makes it easier to comprehend the results from the LCA which is preferable in the interpretation phase (ISO 14044, 2006).

There are three obligatory elements in an LCIA (ISO 14040, 2006);

- Choice of environmental impact categories, category indicators and categorization models
- Assignment of LCI results, i.e. classification
- Calculation of category results, i.e. categorization

The three elements results in a LCIA-result which is also called LCIA-profile. The LCIA-profile could then (optional) be used to calculate the magnitude of the category indicator results related to reference values, i.e. normalization (ISO 14044, 2006).

There are some limitations with LCIA. Firstly, the LCIA only takes the environmental impacts that are stated in the goal and scope into account. It can therefore be said that the LCIA does not give a complete environmental impact assessment of the studied product system (ISO 14044, 2006). Secondly, LCIA does not address the economic and social aspects of a product system (ISO 14040, 2006). Lastly, the LCIA cannot in all cases prove significant differences between environmental impact categories and related indicator results to alternative product systems. The reason why some LCIA studies fail to do that could be for some of the following reasons (could be other reasons as well)(ISO 14044, 2006):

- Limitation of the collected data for all the environmental impact categories.
- Limitations in the LCI-phase such as consciously excluding parts of the product life cycle.
- Limitations in the LCI-phase due to insufficient data quality.

2.2 Circular economy

Circular economy is a term that has become more frequently used recently, many companies and organizations have started to investigate the potential of it. Circular economy has potential to improve the sustainability, not only environmentally but also economically and socially (Geissdoerfer, Savaget, Bocken, and Hultink, 2017). This increase in interest is believed to be related to the increased efforts for sustainability and the insight that the society cannot consume to an unlimited extent. The traditional linear economy with a take-make-dispose strategy comes with limitations such as high prices of new raw material and that it is vulnerable for changes in the market (Ellen MacArthur Foundation, 2013). This has led to that many companies try to adjust their businesses to become more resource efficient and make efforts towards a more circular business.

Despite the growth of interest in circular economy over the last years there is no mutual definition of it. However, there are some common ground in the different definitions. Circular economy is about prolonging and maintaining value of products in the economy and aims to utilize resources to its fullest potential. The Ellen MacArthur foundation describes the three base principles of circular economy as: design out waste and pollution, keep products and material in use and regenerate natural systems (Ellen MacArthur Foundation, 2020). In figure 4, a visualization of different flows in a circular economy is presented. It shows how products and resources can be taken care of in order to extend the lifetime and keep products and materials in the system. The longer the flow back in the system is, the more energy is needed. This means that for instance the technical cycles such as maintenance and reuse/redistribute are to prefer over recycling.

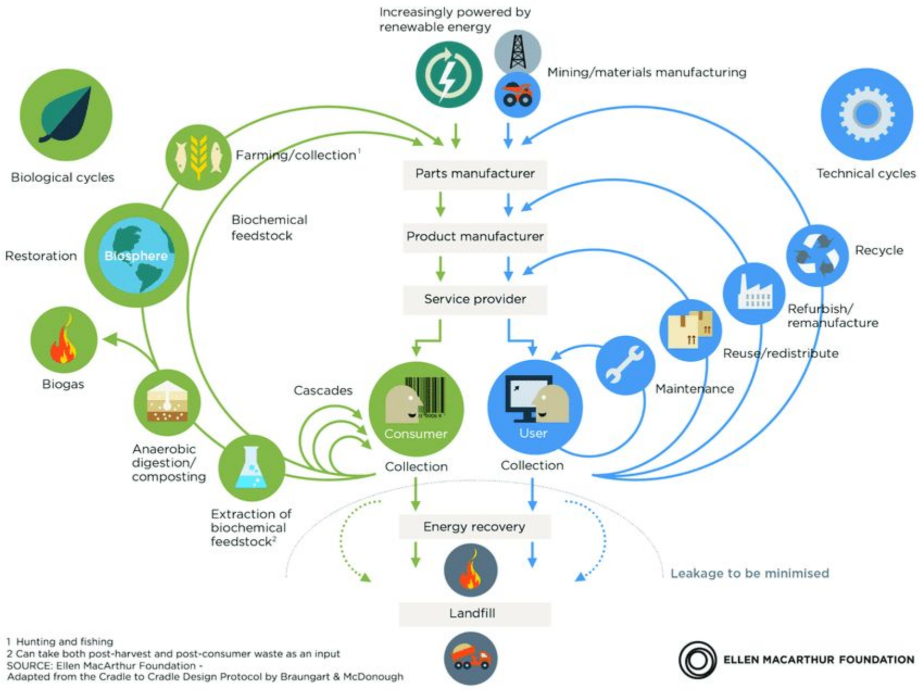

Figure 4. The Butterfly diagram, visualizing the flow of materials, products, components etc. in a circular economy. The closer to the consumer the loop can be recirculated, the less waste of resources (Ellen MacArthur Foundation, 2020). Used on permission of Ellen MacArthur Foundation.

When it comes to circular economy the most discussed aspect is the environmental sustainability and the possible environmental advantages a circular business can have. There is also great financial potential in transforming into a circular business (McKinsey Center for Business and Environment, and Ellen MacArthur Foundation, 2015). Companies that go towards a circular economy has the possibility to extend the value creation of their business and utilize the existing resources in a better way. However, turning into a circular economy also comes with possible economic and structural challenges. A circular business model may lead to difficulties in the supply of material with unstable flows. Further, a circular economy can create a more complicated ownership and incentive structures but it can also create new business markets (Geissdoerfer et al., 2017).

To create a society were circular economy can thrive, support from regulations by authorities and governments are of great importance to enable and create possibilities for circular economy (Geissdoerfer et al., 2017). By supporting circular economy through promotion of sustainable development of both the economy and society, benefits for the environment and sustainability will arise as well.

2.3 Circular business models

For a company or organization to change their business into a circular business, they need a business model that enables and supports circular economy. These business models are different from the traditional business models where value only is created in the beginning of the products life. These circular economy business models (CEBM) are based on systemic and dynamic value co-creation between customer and company.

A circular economy strategy or business model can be described as the element's circular measures, value proposition and value network. Circular measures can be described as actions that can be made to improve the resource efficiency (RE), with other words reduce the losses and use of resources in the life of a product (Böckin, Willskytt, André, Tillman, and Ljunggren Söderman, 2020). These measures can be throughout all the different stages in the life cycle, from the extraction to the post use and end-of-life (EoL) (Böckin et al., 2020).

In the first stages of a products life cycle, the main focus is to reduce waste and losses, both in the extraction of materials and in the production (Böckin et al., 2020). Further, Böckin et. al. (2020) argues that changes in design of products, with change of materials or reduction of material use, can improve the resource efficiency. In the use phase the main target is to improve the efficiency of the use as well as reduce the consumption of auxiliary energy and materials (Böckin et al., 2020). To extend the use of a product, there are different ways to proceed. Maintenance, repairs and refurbishment are some of the measures that can prolong the lifetime of a product. Further it is possible to extend the lifetime through design changes that makes the product more durable. However, to increase the resource efficiency by extending the possible lifetime, it is important that the product is used for the whole lifetime. Great numbers of products are discarded despite that the products are fully functional. To reuse and redistribute used products is of great importance to keep the resources and value of products in the system (Böckin et al., 2020).

In the post-use phase, it is important to recover the energy and material used in the product. This can be done through recycling of the material and use it as input in the production. This will decrease the need of virgin material into the system and production. In this stage there may be tradeoffs where the impact of recycling must be compared with the impact of extracting and producing the material.

Value proposition are the benefits and value that a customer can expect when buying a product or service, in other words how the company delivers value (Fehrer and Wieland, 2020). Unlike the traditional business model where the value is delivered through selling a product, circular value propositions can be created through delivery of services or performance, sharing of assets or helping companies to be branded as eco-friendly. In this way, the value creation is an ongoing process that is present throughout the whole life span.

Moreover, the value network and flow changes in circular business models. Rather than just supply a product to a customer, a circular business can recover and regain value from their products or services. By collaboration with suppliers and customers, it is possible to create value for both parties. What seems to be waste for one stakeholder, may be possible to use as input and resource for another. By rethinking what value is, new networks, propositions and collaborations can create new sources of value through resource integration and value co-creation. Regardless of the goal, moving towards circularity can potentially increase the profit, reduce the environmental footprint or improve the society (Fehrer and Wieland, 2020).

In circular businesses, the design of the supply chain changes. These supply chain flows are reversed and closed compared to traditional models where the flows are one-way. However, these reversed and closed loop supply chains come with some challenges. The reversed flow leads to greater variations in the supply (Fehrer and Wieland, 2020). These variations can be in quality, unstable quantity in supply and problems in timing. Further, it is possible that a business with a reversed supply chain cannibalizes existing market shares.

3. Methodology

The following chapter presents how the project have been carried out. Firstly, the project strategy is described which is followed by the specific case that this project is about. This is followed by a presentation of the LCA method and the data used in it and lastly the approach on how the evaluation of new potential circular business models is presented.

3.1 Project strategy

This thesis is divided into two parts that integrate on a high level. The first part is a life cycle assessment for a LV marine motor and the second part is an evaluation of circular business models. The way the two parts integrate is that the LCA results in the detection of CO_2 hotspots and those are evaluated in the assessment for new ways of providing the LV marine motors more circular.

For this project, a case study research methodology was chosen. This decision to do a case study is based on that a case study is preferable when it comes to answer the questions of “why” and “how” and where the focus of the study is on a contemporary existing phenomenon (Yin, 2009), which correspond well to this project.

Yin (2009) describes the case study methodology as a linear but iterative working method divided into the following six steps; Plan, design, prepare, collect, analyze and share. The including parts of the different steps and the work procedure of this project are explained in the six steps below and visualized in figure 5.

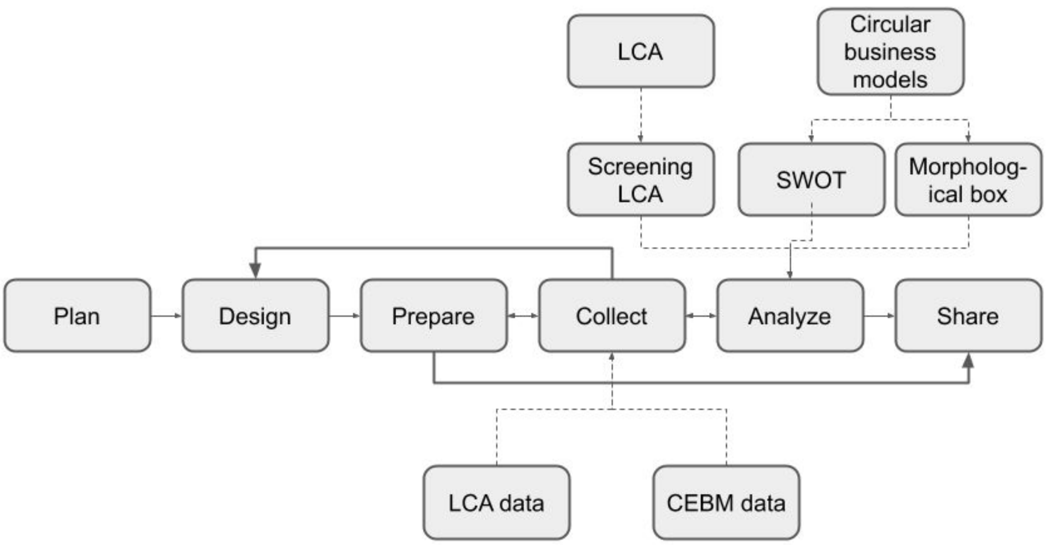

Figure 5. The six steps of a case study, (adapted from Yin, 2009, p.1).

This work procedure method has been performed on both the LCA part of the project and the circular business model part. The two parts aim to answer different questions and the results of the two are to be used for different purposes. With that said, different data and different methods have been used for the two parts of the project which can be read about in the chapters 3.3 and 3.4. As can be seen in figure 5, the circular business model evaluation consists of a SWOT-analysis and a morphological box analysis and the LCA part of the project is a screening LCA that follows the ISO standard 14040/44. The following sub paragraphs describe how to perform the different steps in figure 5, except the parts that have dotted arrows since they will be thoroughly described in chapter 3.3 and 3.4.

Plan

The first part of the study was to plan the project and understand the strengths and weaknesses of using a case study methodology for the project (Yin, 2009). As mentioned earlier, a case study is a good option when the questions of "why" and "how" are to be answered and when the focus is on an existing contemporary case. The planning step of the study was the part where the research questions were identified and the foundation of what the goal of the study will handle was presented. Through the background to the project and a literature study, this part formed a goal of the project and a plan on how to conduct the study.

Design

The design of the research is described by Yin (2009) as the logic that links the data that will be collected in the project to the questions and reason why the study is conducted. It is in this stage where the unit of the analysis and the case of the study was defined and shaped. Further, it is in this stage that the theory, rationale and propositions were developed to support the study. The design of the study is an important way to facilitate the quality of the work in the study.

Prepare

To perform a case study, it was of great importance that the investigators had the desired skills to understand the data that were collected and to be able to ask good and relevant questions. Further, this gathered data desires knowledge and skills of the investigator to interpret the answers of the study in a good way. The preparation stage also included preparation and training in order to perform a case study as good as possible. This included developing and designing a type of study protocol to support the collection of data and the working procedure.

Collect

The collection stage of a case study is the part where all the data were gathered. It is important that the evidence of the data is supported by multiple sources of evidence to ensure the quality of the study. Yin (2009) describes six sources of evidence that can be used to support the study. These six are documents, interviews, archival records, direct observations, participant observations and physical artifacts. For this study, the most commonly used source of evidence was interviews. Semi-structured interviews were conducted with important stakeholders to gather information for the work with the LCA and the business models. The interviews were not designed to just list a structured set of questions, but more as a guided but flowing open conversation. It was important to remain focused on the goal of the interview to answer the existing questions, but also be flexible and adaptable to capture important data and questions that occur in the discussions. Further, the collection of data also included brainstorming meetings with important stakeholders and experts. These brainstorming meetings handled different topics included in the project and was a good way to get inputs and thoughts of the people with experience and deep knowledge in the subject. Examples of meeting templates and structures of meetings are presented in Appendix H.

A case study is an iterative study so during the work of the project, as new information and data were collected the design of the study evolved. This is visualized in figure 5 with the arrow from collect to design.

Analyze
In the analyzing step of the project, the collected data of the study were investigated. Discussion upon the results and findings were made by examining, recombining and testing the data and evidence empirically. Based on the result and findings, conclusions were drawn.

Share
In the last part of the study, the result and findings of the project were presented. In the share step, the evidence provided for the findings and results is of great importance to prove that the study is valid. Further, the audience should be able to draw own conclusions by the content of the shared materials (Yin, 2009).

3.2 Case description

The motor chosen for this project was decided by the project manager in collaboration with different parts of the company with important information and knowledge in the area. The data and information were gathered through interviews with personnel and through ABB's databases.

The motor that was investigated in this project is the low voltage motor M3BP 280 SMB. This is a LV marine motor that is used on ships for pumping water in the harbor. The motor is placed on the open deck and the geographical area of use is mainly in the arctic seas, which demands that the motor is resistant to cold environments, waterproof and corrosion protected. The motor was chosen for this project because of the use pattern, where the motor is only used in the harbor for short periods of time. The estimated operating time of the motor is 2 hours a day, 365 days of the year. It is of high importance that the motor is working when it is supposed to, so the quality is an essential part of the design.

An electric motor is a rotating machine that converts electrical energy into mechanical energy, or more specific, kinetic energy (Hughes and Drury, 2013). The motor consists of two main parts, the rotor and the stator. The stator is a static part in which the rotating part, the rotor, is placed in. The rotor rotates when the magnetic field of the stator interacts with the magnetic field of the rotor which is created when currents are induced in the rotor windings. This generates a magnetic force that makes the rotor rotate which in turn creates an output power from the motor through the rotor shaft.

One property of an electric motor that is of great importance is the efficiency. It can be described as the ratio between the mechanical power from the motor and the electrical input power to the motor (European Union, 2019). The efficiency is calculated as follows;

$\eta_{motor}=P_{out}/P_{in}$ (1)

where: η_{motor} = efficiency of the motor,
P_{out} =output power from the motor,
P_{in} =input power to the motor.

A high efficiency in the energy conversion reduces the energy consumption which leads to lower emissions and costs of operating the electric motor. Depending on the efficiency of the energy conversion, motors can be divided into different efficiency classes (EU, 2019). This classification is formed to reduce the use of inefficient motors and improve the standards of motor efficiency. The classification used for motors are called International Efficiency (EU, 2019) classes and are presented in Table 1 below (EU, 2019).

Table 1. International Efficiency classification for motors.

Code	Efficiency class
IE1	Standard efficiency
IE2	High efficiency
IE3	Premium efficiency
IE4	Super premium efficiency

The motor is a 4-pole squirrel cage motor with a power of 75kW and an efficiency level of IE3, which means 95% efficiency (EU, 2019). The input energy for the motor is generated from a diesel generator on the ship. The diesel generator which is used to provide energy to the motors is assumed to produce 1 kWh per 0,4 liters of diesel (Hanania, Martin, Stenhouse, and Donev, 2015).

The material used in the motor are mainly cast iron, electrical steel (also referred to as core steel), copper and mild steel. There are also some insulation and chrome steel, but this is just a fraction of the total content of material. The motor is divided into four main parts; stator, rotor, housing (incl. bearings) and the rotor shaft which in total gives the motor a weight of 665 kg. The material composition in the different parts and the weight of them are presented in table 2 below.

Table 2. Material composition of the motor divided into the different parts.

	Stator (kg)	Rotor (kg)	Housing, incl. bearings (kg)	Rotor shaft (kg)	Total (kg)
Copper	49,17	12,25	0	0	61,42
El Steel	148,72	88,57	0	0	237,29
Insulation	1,23	0	0	0	1,23
Cast Iron	0	0	348,06	0	348,06
Chrome steel	0	0	1	0	1,00
Mild steel	0	0	0	16	16,00

From now on, in this report, the motor above will be referred to as ABB´s LV marine motor. The report will further be based upon the case with the information regarding usage etc. described in this chapter.

3.3 Life cycle assessment

The LCA method is an iterative method which means that the goals and scopes can change over time (Baumann and Tillman, 2004; Klöpffer and Grahl, 2014; ISO 14040, 2006). Reasons for eventual changes can for instance be data regarding a specific fact is missing and decision makers in the project, i.e. managers, want other information than what is obtained. Therefore, this section of the report will be updated regularly and the questions in the goal part will recurrently be questioned. This section of the report can be followed (used as a guide) regardless of what project that is made since the methodology is based on the ISO standard 14040/44.

3.3.1 Goal

In order to define the goals of the study the following questions are to be answered. The questions are based upon the general description of the goals in the ISO standards 14040 (2006).

Q. What is the intended application of the study?

The intended application of the study in this project is to evaluate if there are possibilities to reduce the carbon dioxide footprint for ABB´s low voltage electric motor, M3BP 280 SMB, during its lifetime.

Q. What is the reason for conducting the LCA?

The reason for conducting the LCA study is to expose potential hotspots for GWP in the above mentioned product system.

Q. To whom is the result intended to be communicated towards?

The result of the study is intended to be presented to the project management who will provide the results to designers and people with skills to change the product system towards the better.

Q. How are the results intended to be used, publicly or internally?

The result of this study will be used internally within ABB in order to make design decisions etc.

3.3.2 Scope

The scope of the study is graphically described in the flow chart of the product system shown in figure 6. The scope is dependent on the goal of the LCA and therefore the following subparagraphs are formulated accordingly. The subparagraphs to the scope are based upon the ISO-standard 14040/44.

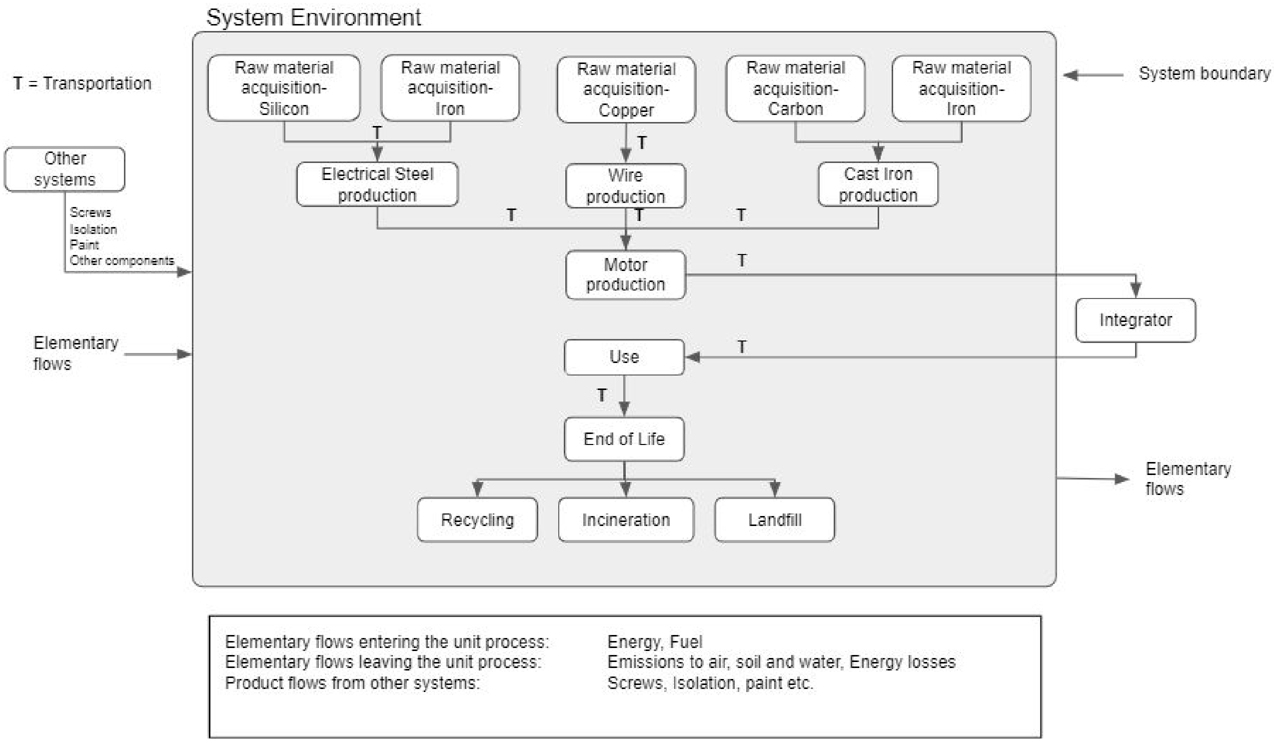

Figure 6. The product system graphically defined with all its functions.

3.3.2.1 Product system

The product system that is to be evaluated is ABB's low voltage motor M3BP 280 SMB, which is used in marine environments such as ports, oil rigs and vessels (ABB, 2016). There are, as can be seen in figure 6, functions that are outside and inside the system boundaries. The functions outside the boundary will be described and motivated in the next paragraph *boundaries*. The product system that is to be studied will be so from cradle to grave which means that the product will be assessed from raw material acquisition to disposal, which includes production and usage. The main goal of the study is to find peaks in global warming potential (GWP) during the motor's life cycle. Therefore, the elementary flows such as material, energy and CO_2 (and equivalents) will be of high importance. The transport is also of high interest since it contributes to emissions. The material that is included in the study is the material that make up most of the motor in percentage, the reason is that those materials most likely have the highest potential impact on the GWP.

3.3.2.2 Boundaries

A system boundary must be established, otherwise an LCA study can become unlimitedly large. The functions that have been decided to leave outside the boundary in this study is; parts that make up smaller components of the motor such as screws, insulations on the wires, paint and plastics. The integrator function is also outside the system boundary. The reason for that is that it is hard to acquire qualitative data from the company(ies) that integrate the motor in their products. The motor is always a part of another product system and there is therefore hard to obtain data regarding emissions, waste etc. from the external companies. The system boundaries are one of the parts of the LCA that is highly dependent on what that is to be assessed and who the results are to be communicated towards. The boundaries are something that will differ between studies and they must be adopted for each specific project.

3.3.2.3 Functional unit

The functional unit is, according to the ISO-standard 14040 (2006 p. 4). the *"Quantified performance of a product system for use as a reference unit."*. The functional unit is based upon the goals and scopes of the study and it should contain answers to the following four questions;

What is to be studied?
How much?
How well?
How long?

The LCA study that is made in this paper is a screening LCA with the main goal to identify hotspots in GWP in the ABB´s LV motor´s life cycle. Moreover, the functional unit is supposed to define what is being studied and all inputs and outputs in the LCI and LCIA are to be related to the FU. In this project the functional unit was initially decided to be defined as; Convert electrical energy to cyclic work within the IE3 efficiency spectrum for its promised lifetime. The reason for mentioning that it was initially decided is because LCA-studies are iterative and the FU can be changed during the project. This functional unit was kept throughout the whole project as it suited the goals and scope of the study.

3.3.3 Life cycle inventory

The next step after deciding the goal, scope, product system, boundaries and functional unit was to collect data and do calculations on the product system. That part is the LCI which was conducted for all the stages for the product system. In this project they have been divided into; material acquisition, component production, transports, motor production, use phase and end-of-life. The method for acquiring data and how to calculate it are described in each respective sub-paragraph followed after the description of the software used (the next paragraph).

3.3.3.1 Software

For acquiring data and to do calculation of the material acquisition, component production, transportation and end-of-life of the product system, the software CES EduPack was used. CES EduPack is a software developed by Granta Design Ltd. and it quotes environmental data from many sources e.g. Ecoinvent, ELCD and US department of energy. According to Granta Design, CES EduPack is not 100% accurate when it comes to embodied energy and carbon footprint but it allows firm distinctions to be drawn. In the software, the Eco audit tool is used. The software is to be used in the early stage of design in order to get a quick overview on the environmental impact a certain product would have (CES EduPack). The validity of the tool depends on the scope of the study. For internal communication that only requests identification of environmental hotspots, CES EduPack is a good and valid option (Gradin and Åström, 2018). For projects and studies that are to be used for external communication, another software and method should be considered to give a more in-depth result with a higher precision of the calculated impact (Gradin and Åström, 2018). However, if the main target is to identify hotspots in the life stages of a life cycle, CES EduPack´s Eco audit tool is a good option.

3.3.3.2 Material acquisition

An electrical motor consists of many components as mentioned in chapter 3.2 and in this project three of these have been assessed in the LCA. The three components are; copper wires, electrical steel sheets and cast iron housing. Copper is the raw material that has been assessed for the wires and in this case 2% of the copper comes from recycled copper, the rest originates from one of Sweden's largest copper mine, Garpenberg. The electrical steel sheets consist of steel which in this case are made of 100% virgin material that originates from a large iron mine, Kursk, in Russia. The iron used for the cast iron housing for the motors comes from the Benxi mine located in the Beijing region. The amount needed to manufacture one motor of each of the above mentioned materials is 61 kg copper, 237 kg electrical steel and 348 kg cast iron. To calculate the effect of the material production, these numbers and geographical areas were used as input in CES EduPack.

3.3.3.3 Component production

CES EduPack was used to calculate the effect that the component production has on the environment by using sources that takes into account what energy mix and which methods that the company that produces the components have. The wires are produced in Sweden and the secondary processes after the extraction of raw material is wire drawing. Sweden's energy mix is 3% fossil fuel with an efficiency of 33%, nuclear energy 47 % and renewable energy 50% (CES EduPack). The electrical steel is manufactured in Russia and the second process after extraction is cold rolling. The energy mix in Russia is 66% fossil fuel with an efficiency of 32%, nuclear energy 16% and renewable energy 18% (CES EduPack). Lastly, the cast iron housing is manufactured in China through casting where the energy mix is 83% fossil fuel with an efficiency of 33%, nuclear energy 2% and renewable energy 15% (CES EduPack).

3.3.3.4 Transportation

The data used for the transports are based on the locations of big suppliers of materials and parts. Furthermore, the supply chain for parts and material is a multi-divided network of suppliers and manufacturers. The transports have therefore been based on the main origin of the materials assessed. The origin data is limited to regions, and the routes of the material transport are based on traditional freight routes and distances. The transportation has been divided into the three main parts of the motor.

As presented in 3.3.3.2, the origin of the copper is the mine in Garpenberg. The Copper is then transported by truck to Nossebro for wire production. This transport is at a distance of 366 km. The truck used for calculating truck transportation is a 6-axle truck, with a capacity of 40 tons. After the production, the wires are transported to the motor production in Vaasa, Finland. This transport is divided into three parts. The first is between Nossebro and Stockholm by truck, the second is by ferry between Stockholm and Helsinki, and the last is by truck between Helsinki and Vaasa. The section between Nossebro and Stockholm has a distance of 408 km, the ferry freight between Stockholm and Helsinki has a distance of 450 km and the last section between Helsinki and Vaasa has a distance of 420 km.

The electrical steel originates, as presented in 3.3.3.2, from Kursk. The material is after that transported to the electrical steel production in Yekaterinburg by train, which is a distance of 2300 km. After this, the parts are transported 2920 km to Vaasa by train.

For the Cast iron housing the mining is, as presented in 3.3.3.2, done in Benxi, China. The raw material is then assumed to be transported by train to Anshan, China, for material and component production. The distance of this transport is 140 km. After the production, the parts and components are transported by train 300 km to the port of Dalian. It is then transported to Helsinki by ship and the route is calculated to go through the Suez canal. This freight accounts for a distance of 22230 km.

The level of uncertainty of the transportation is generally quite high. Because of that, the transports are limited to only one supplier per part, when the real case includes multiple suppliers, the result is not completely representative of the actual impact of the result. However, the chosen transports and routes should give a sufficient overview of the impact of the transportation.

3.3.3.5 Motor production

The production of ABB’s LV marine motors is located in Vaasa, Finland. As of now no data is available except how much of the electric steel that is trimmed during the stancing (10%). Allocation of waste and energy flows from the production has not been able to acquire due to the outbreak of Covid-19.

3.3.3.6 Use phase

The information for the use phase was received from ABB and is a result of assumptions made by the team manager together with customers. The motor specifications, such as efficiency and output power were gathered through detailed specification in product datasheets for the model M3BP 280 SMB. This data is accurate if the motor is operated in the conditions that it is designed for and these conditions are assumed to be followed by the customer.

The operating conditions, such as operating time and years of operation that is presented in 3.2, were something that the sales department of ABB presented. These numbers are hard to quantify and they may differ between different customer but they are estimated to correspond to the real operating conditions as close as possible. There may be a reason to question the assumptions of the operating use, as they may have a significant impact on the result of the LCA. This will further be discussed in the discussion chapter.

3.3.3.7 End-of-life

The end-of-life scenario for the motors today is dependent on the customers. Therefore, information regarding the last stage in the product’s life cycle is relatively unknown. More recently, ABB has initiated a program wherein ABB encourages customers to recycle their motors at the end-of-life. However, in order to understand the influence of recycling, a hypothetical case was considered during this study. It has been assumed, by the project management, that 50% of the cast iron housing gets recycled, 20% of the electrical steel gets recycled and 80% of the copper gets recycled. How this affects the end-of-life potential can be read in the result chapter 4.1.1.6.

3.3.4 Life cycle impact assessment

The chosen impact category of this project was to calculate the climate change, with the climate change factor Global warming potential (GWP). Global warming potential is defined to be the aggregated amount of heat a gas traps in the atmosphere over a specified time horizon, relative to carbon dioxide (Muralikrishna and Manickam, 2017). In this project, the scope is to analyze the carbon footprint of the life cycle of ABB´s LV motor, so this is the only data type that an impact can be calculated on. As the LCA is limited to CO_2, which is the reference point in GWP, the time frame is not of great importance. However, the timeframe used in the impact analysis was chosen to be 100 years.

3.4 Circular business models

To evaluate and design different possible circular business models for the application, multiple existing models in various markets were investigated. These gave inspiration and important inputs to which highlighted the strengths and weaknesses of their businesses. In the following steps, the methods used for evaluating and comparing the different possible circular business models are presented. The methods used in the evaluations of the business models are SWOT-analysis, morphological box of circular business model design and lastly investigating end-of-life potential with the Eco audit tool in the software CES EduPack. The methods could be applied to any project that aims to evaluate circular business models for a product or service.

3.4.1 SWOT-analysis

In order to get a comprehensive overview of the potential positive and negative effects of new ways of providing the LV motors, the SWOT-analysis method has been used. To be able to compare the different circular business models a SWOT-analysis have been conducted for the two proposed CEBM. SWOT is a planning tool that aims to identify strengths, weaknesses, opportunities and threats (Quezadaa, Reinaoa, Palominosa, and Oddershedea, 2019), it can be visually presented as in figure 7. The strengths and the weaknesses are internal e.g. good resources, high competence, bad quality and high prices. The opportunities and the threats are external such as; new technologies, economic climate, competitor activities and political aspects.

Figure 7. The SWOT model visually represented.

3.4.2 Morphological box of CEBM design options

The morphological box of circular economy business models, seen in figure 8, is used as a supporting tool when designing circular business models (Lüdeke-Freund, Gold and Bocken, 2018). When designing a circular business model for a specific business, there is no predetermined model that suits every type of business best. Designing a business model that suits all needs is a creative process and the morphological box of CEBM design options is a tool that can provide assistance in identifying values and options of models.

In the following subheadings for CEBMs, designs are described through the morphological box. The box has derived from an analysis of 26 CEBMs made by F. Lüdeke-Freud *et. al.* (2018) and its codes are what is seen as a number in each box. These codes can be found in appendix G which is Lüdeke-Freud's lists of CEBMs.

BM Dimensions		CEBM design options derived from reviewing 26 CEBMs (the number of CEBMs that mention the respective design option is indicated in parentheses)[a]										
Value proposition	Products	Repaired, refurbished, remanufactured, or recycled products (3)	Reusable or recyclable products (3)	Products based on recycled waste (3)	Long-lasting products (3)	Used products, components, materials, or waste as production inputs (5)	Reusable or recyclable production inputs (1)					n.s. (9)[b]
	Services	Facilitating collaboration (3)	Take-back management (4)	Customer education (3)	Waste handling, processing (3)	Product-/service-based functions (2)	Maintenance, repair, control (4)	Product-/service-based results (1)	Upgrading (2)	Auxiliary services (2)		n.s. (11)
Value delivery	Target customers	Quality-conscious customers (1)	Cost-conscious customers (1)	Green customers (2)	B2B customers (4)	B2C suppliers (1)	B2B suppliers (2)	C2C suppliers (1)				n.s. (17)
	Value delivery processes	Connecting suppliers and customers (5)	Providing access to a product's functionality (2)	Providing (product-based) services and results (2)	Providing used products, components, materials, or waste (4)	Taking back used products, components, materials, or waste (4)	Sharing products, components, materials, or waste (2)					n.s. (11)
Value creation	Partners and stakeholders	Suppliers (1)	Manufacturers (5)	Retailers (2)	Service providers (2)	Public institutions (2)	Collectors of products, components, materials, waste (2)	Others (e.g., researchers) (1)				n.s. (17)
	Value creation processes	Maintaining or repairing products, components (6)	Refurbishing or remanufacturing products, components (5)	Recycling of products, components, materials, waste (3)	Upgrading or upcycling of products, components, materials, waste (3)	Reselling products, components, materials, waste (3)	Taking back or recapturing products, components, materials, waste (7)	Winning back base materials (4)	Using used products, components, materials, waste as input (8)	Matching over- and under-capacities (4)	Designing products, components, materials (4)	n.s. (1)
Value capture	Revenues	Additional product revenues (3)	Payments per unit of service (5)	Payments for functions or results (1)	Price premiums (6)							n.s. (12)
	Costs	Labor (1)	Repair, maintenance, control (3)	Waste handling, processing (7)	Manufacturing (1)	Resource inputs (13)	Transportation, logistics (1)	Supply risks (1)				n.s. (11)

Figure 8. The morphological design of the CEBM box. Used with permission of Lüdeke-Freud et. al (2018)

3.4.3 Examples of existing CEBM

There are several examples of companies that have implemented successful and highly profitable CEBMs in their everyday operation. Some of these companies will be described and evaluated in the following paragraphs. The reason that these companies are described in this report is that the designs of their models have been an inspiration for the two proposed CEBMs for ABB's providing of LV motors to their customers, see chapter 4.2.

CAT Reman

Caterpillar has, for almost 50 years, had a business model were old products are taken back and processed in a remanufacturing line (Caterpillar, 2020). The result is products that are "as good as new" which are sold to a price that is on average 40% cheaper than a new product with the same function and performance. The model also includes an incentive system where a deposit function makes the customer more willing to return and buy new products when the product is consumed. The products are sold with the same warranties as new products from Caterpillar to ensure customers that the proper function of the remanufactured products (Caterpillar, 2020).

Rolls-Royce

The British aircraft turbine and engine manufacturer has a business model where they do not sell their motors, instead they sell the function of the motors as "Power by the hour". In their model the manufacturer keeps the ownership of the product and therefore design it so that service and refurbishment/remanufacturing is easy to perform. The customer pays for the time that the engines are operating, and the responsibility for motors' performance is on Rolls-Royce. The model also contains a profitable service package for Rolls-Royce (Rolls-Royce, 2020).

SKF

SKF is one of the world-leading provider of bearings and have changed their business model from a traditional business where they sell bearings towards selling the function of motion. Through smart monitoring and maintenance, they provide bearings that they are responsible for to work, which minimizes the risks of harmful bearing breakdowns and sudden unexpected costs (SKF, n.d.a, n.d.b]. This kind of business where customers buy a function or service instead of a product is called a product service system (PSS). The customer buys the function of motion, and SKF provides the best suiting solution and has the responsibility for it to work. Further, SKF offers the service of refurbishing old bearings. This reduces the cost of the bearings, the material use and the lead times at the same time that they offer bearings that are as good as new ones (SKF, n.d.a).

Kyocera/HP/Ricoh

Many of the biggest companies in the printing industry have changed their businesses from selling printers and ink to selling a printing solution where the customer pays for the actual printed documents as a subscription (HP, 2020; Kyocera, 2019; Ricoh, n.d.). This is also a kind of a PSS because the customer does not need to pay for the printer, but for the function of printing. The printing companies has also redesigned their printers so that maintenance and repairs are easier to perform. Screws and bolts are standardized and parts are designed to be replaced so that the life of the printers can be extended.

Maersk

The world's largest company in container shipping has started to implement "product passports" for their ships in order to facilitate the recycling of the material at end-of-life. By increasing the information about the different parts, the recycling will be both cleaner and more efficient and can provide a supply of steel and other materials for the production of new ships (Ellen MacArthur Foundation, 2017b).

4. Result

In this chapter the results of the study are presented. The result chapter is based upon the LCA and the circular business models and are presented in two parts. The two parts are divided into relevant sub-paragraphs that follows the order in which they were performed.

4.1 LCA

The result of the life cycle assessment is divided into two main parts. The first part is a life cycle inventory where the data collection and the data calculations are presented. The second part is the life cycle impact assessment where the possible impacts of the product system are presented. The results from the LCA cannot be used in any other context than the one in this report since it is a screening LCA with the purpose of being communicated internally. However, the results can be of good use for comparing the work procedure in other projects.

4.1.1 Life cycle inventory

The LCI of the life cycle assessment performed in this report are described in the following paragraphs. These consists of gathered data and calculated results. The results will be presented in the six subcategories; material acquisition, component production, ABB motor production, transportation, end-of-life and use-phase. The first five of these categories are calculated in the ECO audit tool in the software CES EduPack, the complete detailed reports can be found in appendix A-F. The use-phase is calculated by hand with relevant facts and assumptions, presented in chapter 4.1.1.5. Lastly, the result for the complete result from cradle to grave is presented.

4.1.1.1 Material acquisition

The result of the material acquisition is based on the material and the weight of the material. The extent of how much that is recycled are included in the calculation. For electrical steel, the total footprint of the production is calculated to be 634 kg of CO_2. For the copper, 2% of the material used in the motor is recycled copper. The result of the material acquisition for the copper was calculated to 219 kg of CO_2. Lastly, the electrical steel was calculated to account for a carbon footprint of 899 kg. The sum of these materials is a total of 1752 kg of CO_2. The result for the material acquisition is presented in figure 9.

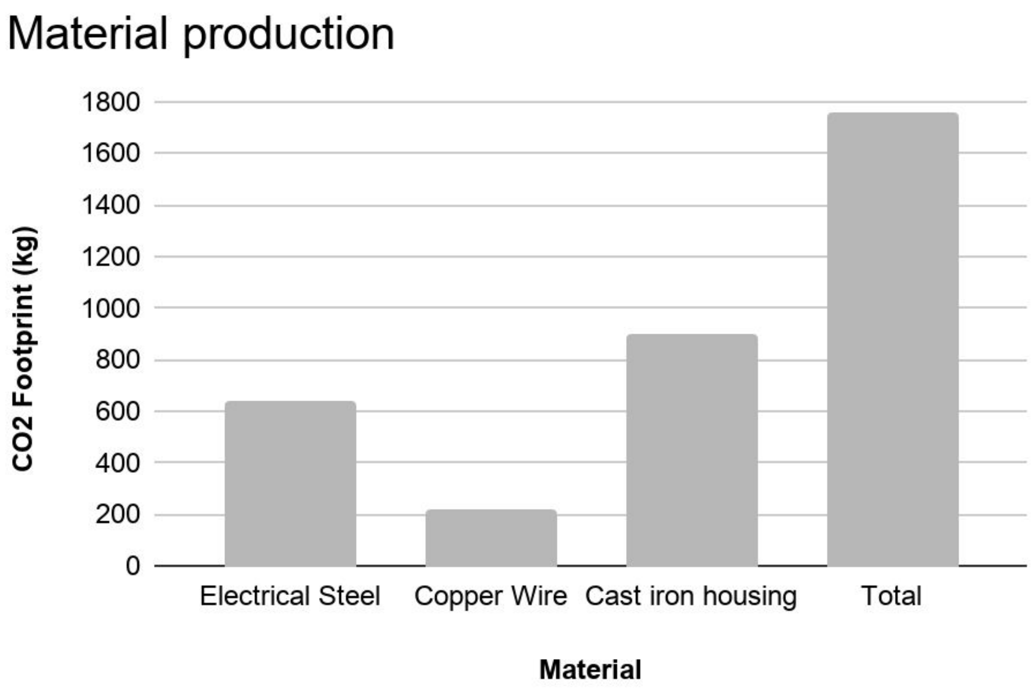

Figure 9. The CO_2 footprint for the different parts of the motor during material production.

4.1.1.2 Component production

The result of the component production is based on the numbers presented in 3.3.3.3, with the energy mix and the material process. Based on these numbers, the total effect of the components was calculated. For the copper, the result was 16,6 kg of CO_2. The footprint of the electrical steel was calculated to 82,9 kg of CO_2. Lastly, for the cast iron housing, the CO_2 footprint was calculated to 283,0 kg of CO_2. The different manufacturing steps for the motor accounts for a total effect of 382,5 kg CO_2 and are presented below in figure 10.

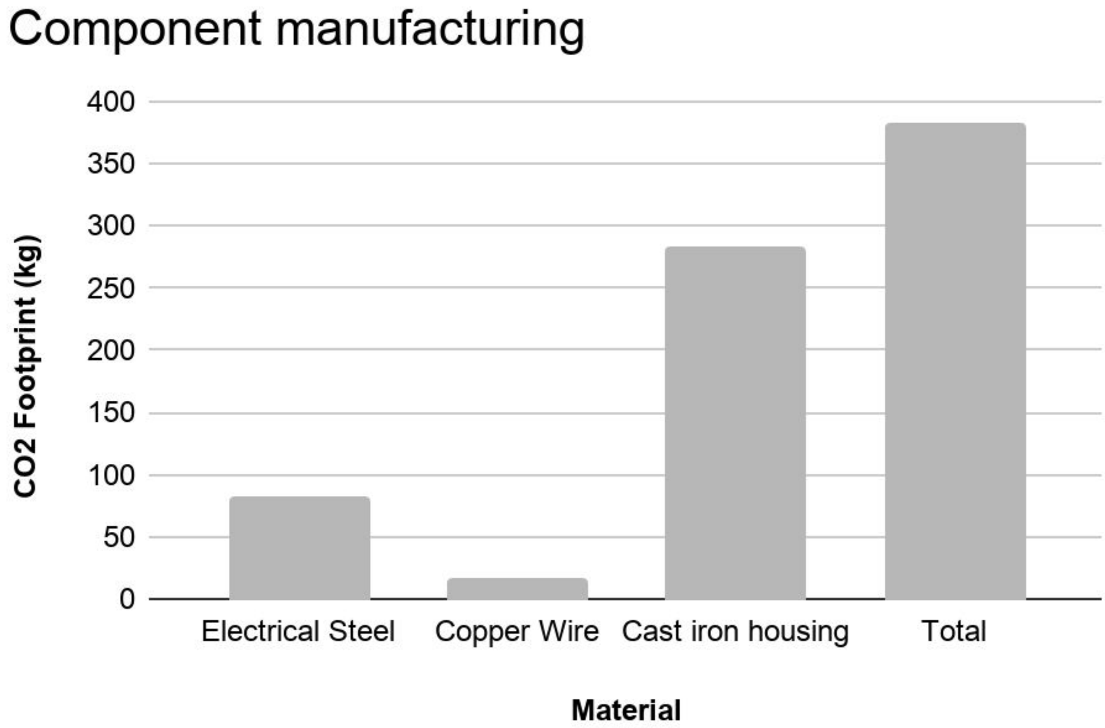

Figure 10. The CO_2 footprint for the different parts of the motor during the component manufacturing.

4.1.1.3 ABB-motor production

As mentioned in 3.3.3.5, this result was not possible to calculate to the desired extent. The only data available were the stancing of electrical steel. For this process, 10% electrical steel goes to waste when the plates get stanced. This creates a loss that need to be compensated in the earlier stages of the life cycle and 10% more electrical steel must be produced and transported to Vaasa.

4.1.1.4 Transportation

The carbon footprint of the motor was calculated with CES EduPack. These are based on the distances, freight types and weight and are presented in 3.3.3.4. In figure 11 below, the separate parts and the total footprint are presented. The CO_2 footprint for electrical steel was calculated to 18,7 kg per motor. For the copper wire, the footprint was 3,8 kg. Lastly, the carbon footprint for the transportation of the cast iron housing was calculated to 100 kg. This resulted in a total carbon footprint of the transportation of the motor of 123 kg CO_2.

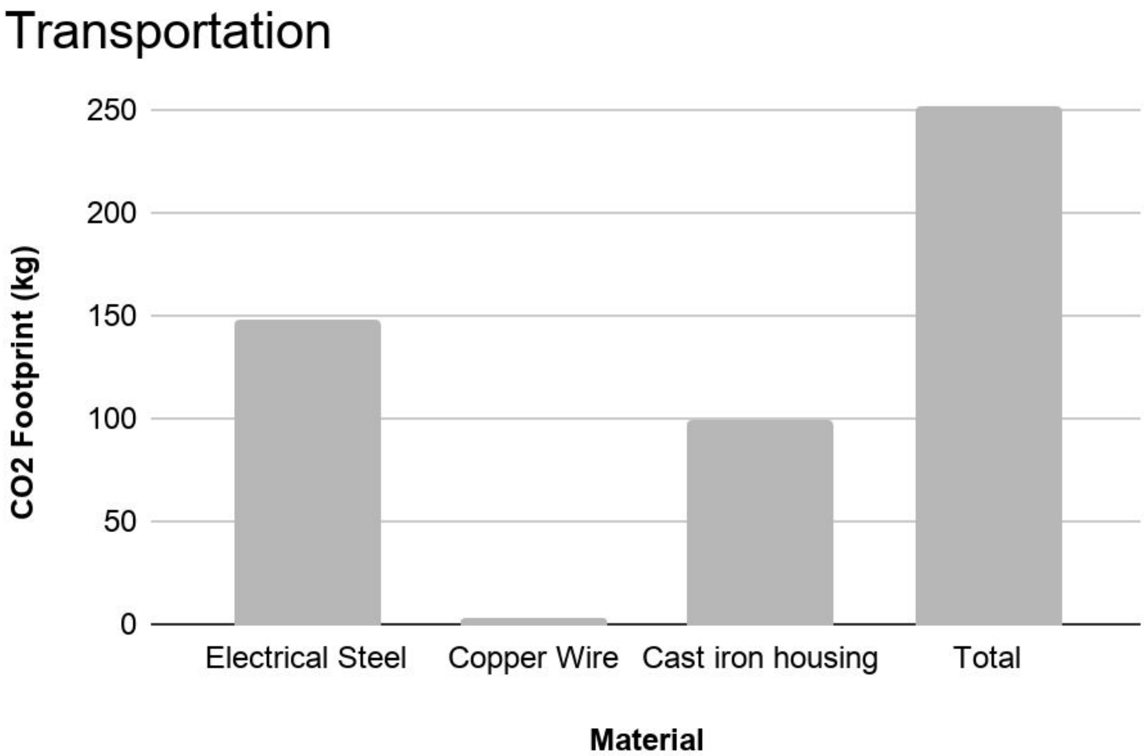

Figure 11. The CO_2 footprint for the different parts of the motor during the transportation.

4.1.1.5 Use-phase

To calculate the impact of the use phase of the motor, calculations by hand had to be made. The energy needed to run the motor for five years with an output of 75 kW and with the specified efficiency was calculated with the following energy calculation:

$$Energy_{motor} = (P_{Out} * Total\ operating\ time) / \eta_{motor} \tag{2}$$

where: $Energy_{motor}$ =Energy consumption motor,
P_{out} =output power from the motor,
η_{motor} = efficiency of the motor.

This resulted in a total energy consumption of the motor of 288 158 kWh, and the number used for the calculation is presented in table 3. To provide this energy to the motor there is, as mentioned in 3.2, a diesel generator. To calculate the carbon footprint of the use phase of the lifetime of a motor, this must be taken into account. As presented in 3.2, the average consumption of diesel for the generators to produce 1 kWh is 0,4 liter. The carbon footprint of one liter of diesel is 2,66 kg CO_2 equivalents (SPBI, 2019). The calculation for the total carbon footprint for the complete lifetime is calculated as follows:

$$CO_2 footprint = Energy_{motor} * (Diesel\ consumption / kWh) * (CO_2 footprint / l\ diesel) \quad (3)$$

This resulted in a total carbon footprint of the use phase for ABB´s LV marine motor of 306 600 kg. The numbers are presented in table 3 below.

Table 3. The values used for the calculation of the impact for the use phase.

Use phase	
Efficiency	95%
Output [kW]	75
Working [hr/day]	2
Days running/year	365
Years of operation	5
Energy [Kwh/lifetime]	288157,9
Average consumption for diesel generators [l/kWh]	0,4
Carbon footprint [kg CO_2/l diesel]	2,66
Carbon footprint per lifetime [kg]	306600,0

4.1.1.6 End-of-life

For the End-of-life phase in the life cycle of ABB´s LV marine motor, the data is divided into the three main material categories electrical steel, cast iron and copper. The recycled content of these are assumed, as mentioned in 3.3.3.7, 20% of the electrical steel, 50% of the cast iron and 80% of the copper. It is further assumed that 2% of the copper is reused in the production of new motors.

In the CES EduPack there is a function that presents the End-of-life potential, which presents the possible deduction of the total impact from the different steps. These are based on how much of the content and in which way that the material is brought back to the system. As presented in 2.2 and the butterfly diagram in figure 1, the closer the loop, the bigger potential of saving resources and energy. In table 4 below, the numbers of the EoL-potential are presented.

Table 4: The end-of-life potential of the different materials.

	Cast Iron	Copper	Electrical steel	Total
EoL-potential (kg CO_2)	−320	−77	−94	−491

4.1.1.7 Cradle-to-grave

For the result of the total life cycle of the motor the use phase has by far the biggest footprint of CO_2 and accounts for 99,2% of the total footprint. The second largest step of the life cycle is the material acquisition, with 0,6% of the total footprint. Both the manufacturing stage and the transport accounts for about 0,1% each and the end-of-life only 0,01%. The total footprint of the life cycle, from cradle-to-grave, was calculated to 309 007,8 kg CO_2. The compiled result from the LCA with the percentage of the total CO_2 footprint and the total emissions of CO_2 are presented in table 5, and a visualization of the share of the total footprint is presented in figure 12.

Table 5. The total carbon footprint of the steps in the life cycle of the motor.

	Material	Manufacture	Transport	Use phase	End-of-life
kg of CO2	1755	382,5	251,8	306600	18,5
% of total CO2 footprint	0,6%	0,1%	0,1%	99,2%	0,01%

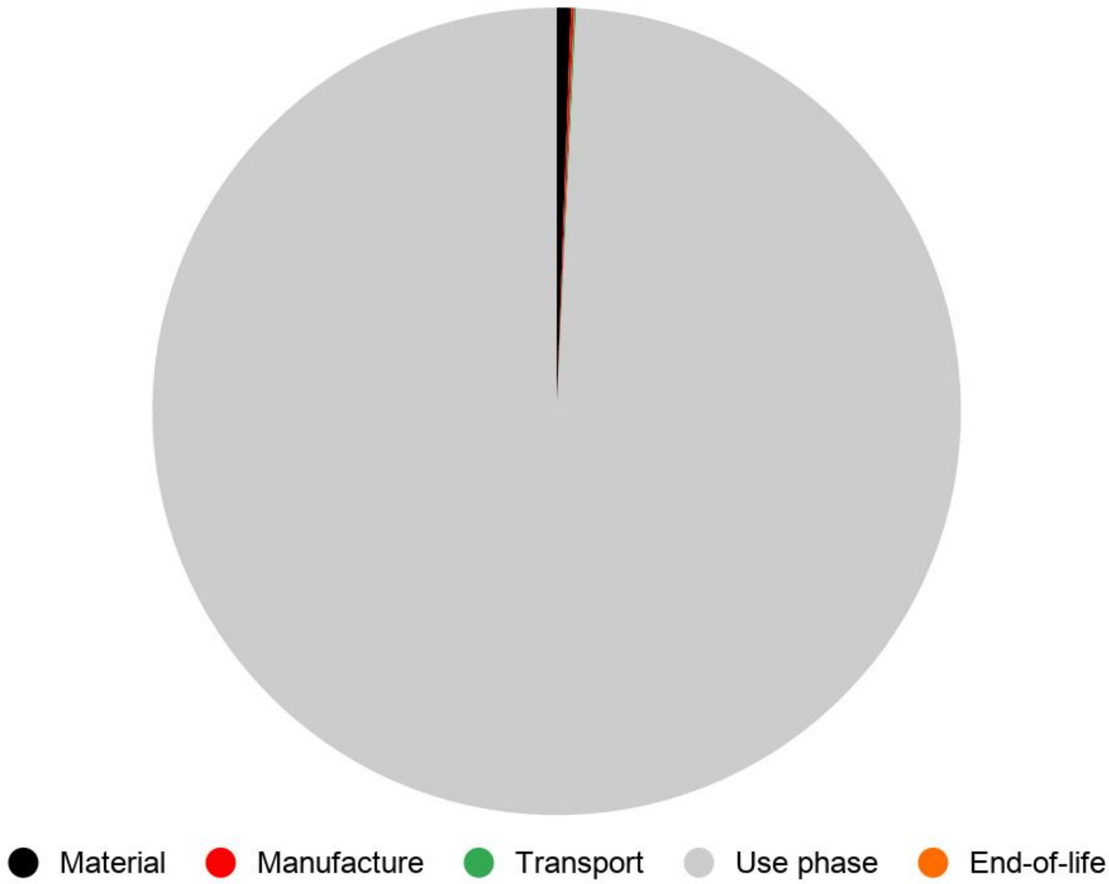

Figure 12. A circle diagram with the shares of the different steps of the life cycle.

4.1.2 Life cycle impact assessment

The impact of the life cycle is calculated in the LCIA. As stated in 3.3.4, the only chosen impact category was climate change, with the factor GWP_{100}. Because of that the carbon footprint was the only calculated effect of the life cycle, this was translated to global warming potential. The conversion from CO_2 to GWP_{100} has a ratio of 1:1, so the CO_2 can be converted directly from kg CO_2 to GWP (Muralikrishna and Manickam, 2017). This resulted in the numbers presented in table 6 below.

Table 6. The GWP_{100} for the life cycle.

	Material	Manufacture	Transport	Use phase	End-of-life	Total
GWP	1755	382,5	251,8	306600	18,5	309007,8

The impact of the life cycle of ABB´s LV motor on climate change was as presented 309 007,8 in GWP_{100}.

4.2 Circular business models

The collection of data regarding designs of circular business models used by various companies has been an inspiration to the following proposal of CEBMs for ABB´s LV motors. Furthermore, brainstorming and interviews were continuously performed with experts at ABB with relevant knowledge and expertise about the project and its content, for instance the material of the LV motor M3BP 280 SMB. The brainstorming lead to two different CEBM. The first suggested model is based upon remanufacturing and refurbishment and the second model is based upon selling a function rather than a product i.e. a product service system. The two models are highlighted in the bullet list below;

- *Business model 1 - The refurbishment/remanufacturing model*
- *Business model 2 - The product service system model*

These two models are in the early stage of development and consists of many assumptions and simplifications. As the project has moved on, discussions about these assumptions and simplifications have gone back and forth with the decision-makers in the project. The two suggested CEBM have been described and evaluated with both the morphological CEBM-box and the SWOT-analysis method. The result is presented in the following sub-paragraphs. At the end of each CEBM, there is a sub-paragraph where the CEBM is connected to the LCA in order to see potential savings in GWP. The resulting two CEBM, which were based on the work procedure described in chapter 3.4, could be good for comparison if similar projects are performed by other practitioners.

4.2.1 The refurbishment/remanufacturing model

The first proposal for a business model with the goal of providing ABB’s LV motors in a more circular manner is the refurbishment/remanufacturing model. The inspiration for business model (BM) 1 has roots in the companies with business models, such as Caterpillars Cat Reman in chapter 3.4.3, which includes taking back their own products, repair/remanufacture/refurbish and then sell them with a discount. Since the product is an electrical motor, which has many applications, it must not be used in the original settings which in this case is marine use on ships. The reason why that is brought up is that the outer strains in the marine environment on the motors set high requirements on the motors regarding corrosion protection etc. Therefore, it is relevant to assume that these motors could be cascaded into other applications since they might have lost some of the protection towards the extreme conditions in the marine surroundings.

The business model is to include incentives for customers to return the motors when they are done using them. The reason for the incentives is to reassure that the motors are returned to the company so that they can go into the process of being restored or stripped for parts. It is important to have the motors coming back since the BM require a production line that handles the old motors. If the input flow of discarded motors fluctuates too much and or is to low it would require an extremely flexible production line which might be hard to achieve. In order to make the BM profitable, the motors must be designed in a way that simplifies the possibility to remanufacture/restore/refurbish the motors, i.e. design to disassemble. It is necessary to be able to easily restore the motors, otherwise the man hours required to do the job increase the costs of the restoration so much that it would eat up the potential profits (the motors are a relatively low-cost product).

The motors today are considered to be used for around five years, but they are designed to last for 20 years. This is a wasteful way of using the motors but it also makes the BM 1 more lucrative since it would mean that many of the motors going back into the company should be in good shape and therefore easier to restore.

BM 1 requires a well-functioning supply chain that works in both ways in order to be able to supply customers with motors and the own manufacturing plant with old ones. A supply chain of that sort could be tough to achieve but ABB have an advantage here since they are such a large company that already operates in over 100 countries (ABB, 2020a).

4.2.1.1 SWOT-analysis BM 1

The potentials and risks connected to using BM 1 for ABB’s LV motors is thoroughly evaluated in a SWOT analysis, as described in chapter 3.4.1. The results of the analysis are divided in internal and external potentials and risks as seen in figure 13. The content is further described under the figure.

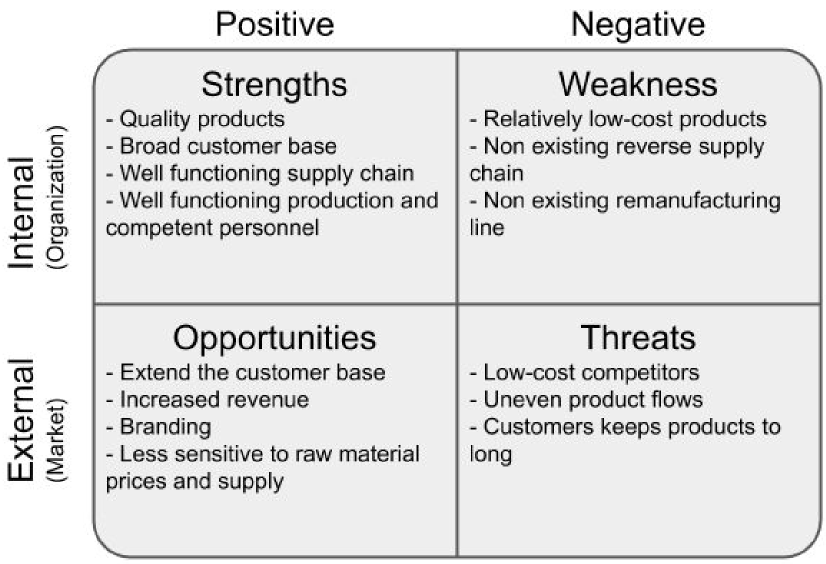

Figure 13. The SWOT-analysis of BM 1 visualized.

Internal - strengths
ABB is a large, well established company within the electrical motor sector. One of their main competitive advantage today is their high-quality products. In a business model as BM 1 it is advantageous to have high quality products. A product of high quality is easier to predict how and when it is breaking down and which parts that needs to be repaired/exchanged. Refurbished or remanufactured high-quality products are more likely to be accepted by the customer since the customers have higher confidence in that the quality of the product is restored to a well-functioning level and performance. For products that have low quality from the beginning in comparison would most likely have problem with convincing customers that their restored products meet the expected level of performance and quality.

Another positive effect of being a well-established company in its sector is the broad and large customer base. Since ABB have been around for a long time, they have developed a large and broad product portfolio. This is positive when implementing a new business model. Firstly, the company can target a small part of the business and have the BM 1 tested out as a pilot project. Moreover, specifically for BM 1, there are potentials in cascading the used LV motors into other applications than the marine use. The motors are exposed to highly corrosive environments and there is a risk that the outer parts of the motors get worn out. The motors that have been taken back might no longer be suitable for harsh environments, but they might be well suited for other applications with less outer strains.

The last internal strength that has been highlighted in the SWOT-analysis of BM 1 is the well-functioning production and the competent personnel. ABB's production of their LV motors is very good, they have a production that is well developed and it is in a mature state.

There are several reasons why a mature production is advantageous when introducing new lines; one is that in a mature production there are very good understanding for the products and the way there are built. Another reason is that new pilot lines can be introduced without harming the production flow, there are more room for experimenting. The strength of ABB's manufacturing sector is that the production steps of the motors have been developed and optimized over a long period of time. That expertise on the production can then be applied in the pilot line for remanufacturing the motors. Furthermore, well trained and experienced blue collar workers can be argued to be crucial to create operational stability (Liker and Convis, 2012). This source of expertise and experience can play a huge role in making a profitable remanufacturing line. The workers both have knowledge about the production steps and quality expertise when it comes to which parts that are good/bad and can or cannot be reused.

Internal - weaknesses

Several potential internal weaknesses at ABB has been discussed when evaluating the BM 1 for the LV motor. Firstly, the products that are to be restored have a relatively low acquisition price compared to the cost of using the product during its lifetime. It can be seen in the LCA results that the motors require approximately 90 000 liters of diesel fuel (combusted in the diesel generator) during its entire use phase. The purchase price of the LV motor compared to the cost of 90 000 liters of diesel (in 2020 according to the U.S. energy information administration (U.S Energy information administration, 2020)) is in the price range of 2500$ (Electrotech drives: Turning industries, 2018) compared to 60 000$. The price for diesel is at the moment extremely low in comparison to previous years due to the current world economic state. To be closer to the reality over years the price for the fuel should be around ⅙ higher. It must also be mentioned that there are other costs associated with the operation of a diesel generator such as maintenance etc. With that in mind, the cost for operating the electrical motor should be around 75 000$. It can then be calculated that the price for acquiring the motor is only 3,3% of the price for running the motor. Due to the low cost, customers might not be interested in a restored motor which cost less than a new since it over time have low effect on the total investment.

Another internal weakness discovered during the SWOT-analysis was that ABB currently have no existing reverse supply chain. That means that the do not have the logistics for taking back discarded motors. To organize such a supply chain demands investment in both time and money. The reverse logistic might require that new business arrangements must be established (with outside companies) which is both time consuming and critical since the potential new partners would be dependent on the new arrangement.

Lastly, the final internal weakness that was found was the absence of a remanufacturing line. This can be argued to be the largest weakness since to launch such a production line would require large investment. The investment will not only be machines etc. but also space, time and personnel. As mentioned previously in the internal strengths ABB have high skilled blue collar workers. Some of these must be put on the new line which requires new hiring in the production of the new motors (the current production line). Hire new personnel is always a costly and demanding procedure (Centre of Economics and Business Research, 2014). A new line in the manufacturing plant requires a lot of work for the white collar workers as well since they must handle all the planning including staffing, new hiring, production planning, etc. Furthermore, a remanufacturing line most probably requires more space than a production line for new motors. The reason for that is that there are more steps in a remanufacturing line; line-up old motors, disassemble, sort out, restore parts and after that do the entire assemble that takes part in the conventional production line. To conclude, there are many investments required for ABB since they do not already have a remanufacturing line.

External - opportunities
To expand the business towards refurbishing and remanufacture old motors, will extend the customer base. Refurbished motors will be sold for a lower price compared to new motors, which will lead to that cost conscious customer that previously bought a cheaper motor from another company because of the price, can buy a refurbished quality motor from ABB instead. This will broaden the customer base and in same time most likely lead to more sold motors and higher profits.

Further, changing towards a business model were the resources are taken care of in a more efficient way and were the company shows commitment towards circularity and sustainability can give ABB a better environmental branding. ABB will be perceived as a company that cares about the environment and in times where the environment and sustainability is of great importance for many customers this can be a key factor for choosing their products.

To change towards a business where old motors and material are taken care of and restored to its original condition, big cost-savings can be made in material costs (Deng, Liao, Xu, and Liu, 2017). New revenue streams and new profit opportunities can be created, and the total revenue from a motor throughout its lifetime can be increased. Moreover, a company that has a reversed supply chain with material, components and products flowing back to the production is less sensitive to volatile and unstable supplies and prices of raw material.

External - threats
In the SWOT-analysis, some external threats were found. Firstly, the target of reaching customers in lower price business segments may be difficult due to other low-end competitors. These other companies might provide even cheaper motors and therefore this new customer base might be hard to reach. Moreover, a cannibalization of own market shares is a risk if the customers that previously bought new motors found interest in buying refurbished and manufactured motors instead (Godwin Barnabas et al., 2015). This will be a problem if the profit of selling refurbished motors is lower than the profit of selling new ones.

Another threat for BM 1 is the calculation and reliability of ingoing material from the customers. The flow of discarded motors back to the company is hard to calculate in advance and the quality of the ingoing goods may also vary a lot from products to products (Godwin Barnabas et al., 2015). This makes the input flow very dependent on the customer behavior.

Further, the last identified threat in the SWOT-analysis was also connected with the material and product flow back to the company. BM 1 are dependent on that there is a steady flow of old products back to the company, and if the customer keeps the products for a to long period of time, the supply back to the company may be a threat.

4.2.1.2 Morphological CEBM-box

The design of BM 1 is summarized in the CEBM-box seen in figure 14. Each design option that is included in BM 1 is marked with a red circle. A thorough description of the box and its marked content follows after the figure.

	BM Dimensions	CEBM design options derived from reviewing 26 CEBMs (the number of CEBMs that mention the respective design option is indicated in parentheses)[a]										
Value proposition	Products	Repaired, refurbished, remanufactured, or recycled products (3)	Reusable or recyclable products (3)	Products based on recycled waste (3)	Long-lasting products (3)	Used products, components, materials, or waste as production inputs (5)	Reusable or recyclable production inputs (1)					n.s. (9)[b]
	Services	Facilitating collaboration (3)	Take-back management (4)	Customer education (3)	Waste handling, processing (3)	Product-/service-based functions (2)	Maintenance, repair, control (4)	Product-/service-based results (1)	Upgrading (2)	Auxiliary services (2)		n.s. (11)
Value delivery	Target customers	Quality-conscious customers (1)	Cost-conscious customers (1)	Green customers (2)	B2B customers (4)	B2C suppliers (1)	B2B suppliers (2)	C2C suppliers (1)				n.s. (17)
	Value delivery processes	Connecting suppliers and customers (5)	Providing access to a product's functionality (2)	Providing (product-based) services and results (2)	Providing used products, components, materials, or waste (4)	Taking back used products, components, materials, or waste (4)	Sharing products, components, materials, or waste (2)					n.s. (11)
Value creation	Partners and stakeholders	Suppliers (1)	Manufacturers (5)	Retailers (2)	Service providers (2)	Public institutions (2)	Collectors of products, components, materials, waste (2)	Others (e.g., researchers) (1)				n.s. (17)
	Value creation processes	Maintaining or repairing products, components (6)	Refurbishing or remanufacturin g products, components (5)	Recycling of products, components, materials, waste (3)	Upgrading or upcycling of products, components, materials, waste (3)	Reselling products, components, materials, waste (3)	Taking back or recapturing products, components, materials, waste (7)	Winning back base materials (4)	Using used products, components, materials, waste as input (8)	Matching over- and under-capacities (4)	Designing products, components, materials (4)	n.s. (1)
Value capture	Revenues	Additional product revenues (3)	Payments per unit of service (5)	Payments for functions or results (1)	Price premiums (6)							n.s. (12)
	Costs	Labor (1)	Repair, maintenance, control (3)	Waste handling, processing (7)	Manufacturing (1)	Resource inputs (13)	Transportation, logistics (1)	Supply risks (1)				n.s. (11)

Figure 14. The morphological CEBM model for BM1(Lüdecke-Freund et al. 2018). Reprinted with permission.

Value proposition
The business model dimensions that are included in the value proposition are products and services. The design of BM 1 involves taking back and restore old motors and therefore the first circle in products and the second in services are circled. The second circle in the product dimension is long lasting products. That dimension is marked since it is advantageous in BM 1 to have motors that are long lasting when having a model where they are to be restored to a condition "as-good-as-new". The last product dimension that is circled is the reusable or recycled products as input. The reason why that dimension is circled is because BM 1 will include a remanufacturing line in the production and the input to this line will be old motors. The last service dimension that is circled is upgrading and the reason for that is because when the old motors are restored they will, if possible, be upgraded as much as possible. Motors are long lasting products and the in the BM 1 case it is said that the motors will be used for five years and then they will be circled back into production. Five years is a relatively long period and it is possible that LV motors evolve during that time and therefore it is important to upgrade the motors as much as possible in the remanufacturing line in order to stay competitive.

Value delivery
For the value delivery, the included business model dimensions are target customer and value delivery processes. Because of the design of the business model with the reduction of price, one of the target customer groups is the cost-conscious customers. This is why the cost-conscious customer box is circled. These customers may be hard to reach with the price of a new motor, but with the lower retail price they may consider buying a quality motor from ABB. The second target customer box that is circled is the green customers. Green customers mean that the customers are conscious about the environmental footprint that the product makes. By investing in a refurbished or remanufactured motor the material and resources for motors are better utilized and taken care of. To reach this customer, the requirement of the efficiency is important because if the motor is remanufactured but has a lower efficiency, the risk is that the total environmental footprint becomes larger than a new motor. The third and last target customer is the B2B customer. B2B stands for business-to-business, which in this case means that the customer is another company that will integrate ABB´s motor as a part to a system.

The first value delivery process that is circled is providing used products, components, material or waste. This is circled because the main idea with this business model is to provide used products which are refurbished and remanufactured. The second box that is circled is taking back used products, components, material or waste. The reason that this dimension is circled is that to provide remanufactured motors, there needs to be a supply of old motors and components into the company.

Value creation
The two dimensions of value creation are partners & stakeholders and value creation processes. The first box that is circled for the partners and stakeholders is the suppliers. The suppliers in this kind of business are both the customers that gives back the old engines and the traditional suppliers that provides new parts. To remanufacture a motor, there may be parts that is hard to restore or remanufacture and must be replaced with a new part to guarantee quality. This is the reason to that the box manufacturers also is circled. The manufacturers of parts are important for the remanufacturing to work. The last box that is

circled is the collectors of products, components, material and waste. Regardless if this is done within the company or from a external company, this partner is a critical stakeholder for this business model to work.

The first circled box for the value creation processes is refurbishing and remanufacturing products and components. This is the main idea of the business model where value is created by restoring the original quality through refurbishing and remanufacturing. The next box that is circled is the upgrading or upcycling of products, components, materials or waste. The thought with this box is that the for the long-lasting products to be up-to-date after many years, there may have to be some upgrading. This can be that some old parts will be exchanged with newer technologies to stay competitive. The third box that is circled is taking back or recapturing products, components, materials or waste. This is essential for BM1 to work smoothly and to be profitable. By taking back old motors, materials and components, these can be used as input for the remanufactured motors. This is important to capture the value that still exist in the old motors.

When restoring old motors one of the main ways of creating value is to win back expensive material. For instance, ABB´s LV motor consists of a lot of copper (61 kg to be exact). The cost of copper is high and therefore stripping and restoring old motors and reusing costly parts is a way of winning back base material and a way of creating value.

The using of old products and components as input is creating value for BM 1 since the entire model builds upon restoring old motors and reselling them. In that case the input is used products and components.

The last value creation process in BM 1 is the designing of products. The designing of the motors has a large role in making BM 1 lucrative. The motors are to be designed in a way that still make them durable but also easy to disassemble since they are to be taken apart and restored. The easier it is to restore the motors the quicker it can be done in the remanufacturing line which will results in higher profits.

Value capture

The capture of value is divided into two BM dimensions: revenues and costs. The revenues that are a result in BM 1 is the additional products revenues. The additional revenues come from that the motors are circled back, restored and then sold once again. How many times that can happen for one motor is dependent on the shape of each motor after it has been discarded by the customer. The costs connected to BM 1 are; labor, maintenance, manufacturing, resource input, logistics and supply risks. Labor is a cost since BM 1 require physical workers, the products that makes the revenue are physical which require all sorts of work e.g. R&D, manufacturing, planning etc. The repair, maintenance and control costs are relevant of BM 1 since production is a part of the business. Maintenance in a manufacturing plant is one of the highest costs connected to production (Muthu, Devadasan, Ahmed, Suresh, and Baladhandayutham, 2000; Koochaki, Bokhorst, Wortmann, and Klingenberg, 2012). Moreover, manufacturing is a cost in BM 1 which is not strange since the motors are to be manufactured. Resource inputs is a cost in BM 1 and the reason for that is because even though the motors are to be restored they will need some new material (how much depends on the condition of each ingoing old motor) in order to make them sellable. The motors are relatively large and heavy products, around 600 kg, and they need to be transported between customers and the manufacturing plant which in turn is costly. The last cost related to BM 1 is the supply risks of old motors. There is a risk that the input and quality flow of discarded motors fluctuate which can lead to stops of the remanufacturing line which is costly.

4.2.1.3 End-of-life potential for BM1

In the End-of-life result of the LCA in 4.1.1.6, the EoL potential of the current model was presented. In the original model, the material was partly recycled which generated a potential of reducing the CO_2 footprint. This analysis was also done with a remanufacturing of 90% of the old products and materials. The inputs used for this calculation is presented in figure 19 below.

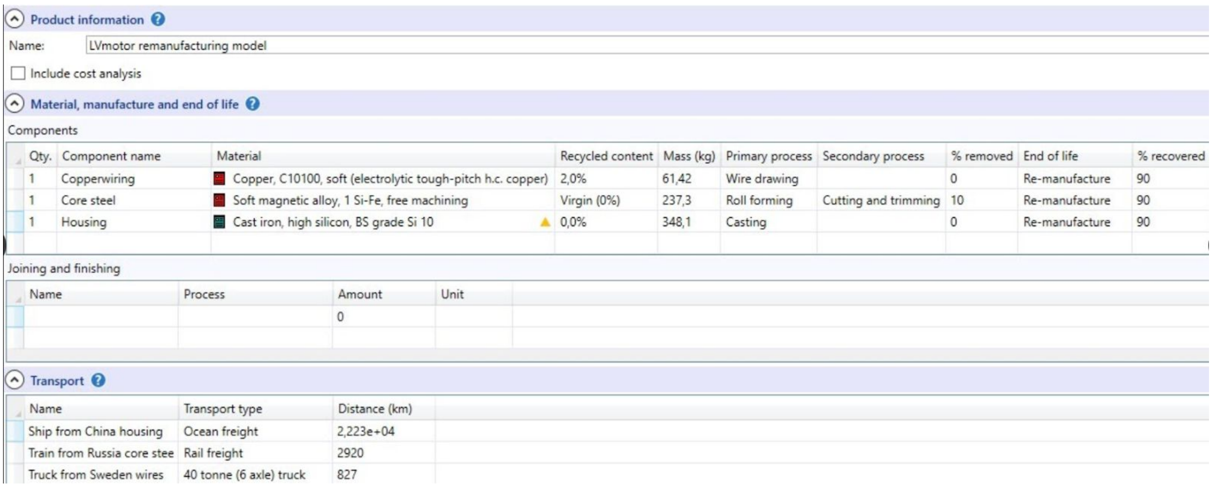

Figure 19. The input for CES EduPack for the remanufacturing model.

The input in the figure are; the component name, the material, recycled content, mass, preliminary process, secondary process, % removed, end-of-life and % recovered. Furthermore, figure 19 shows the input data regarding the transports as well as the name of the product. It is in the end-of-life column that changes have been made compared to the inputs for the current situation. The column was changed from recycled to re-manufactured and the % recovered was also changed. This calculation resulted in an increased potential of reducing the total footprint of the motor with 1450 kg of CO_2. The EoL-potential of BM 1 and the different materials are presented below in table 7.

Table 7. The EoL-potential for BM1, with a remanufacturing of 90%.

	Cast Iron	Copper	Electrical steel	Total
EoL-potential (kg CO_2)	−740	−190	−520	−1450

Compared with the original model with its potential of -491 kg CO_2, the potential of the remanufacturing model is almost three times bigger with -1450 kg CO_2. Further, this potential of reducing the footprint with 1450 kg CO_2 accounts for a reduction of the carbon footprint of the life cycle, without the use phase, with 60%.

4.2.2 The PSS model

The second circular business model proposal for providing ABB´s LV motors is the product service system model. The model has evolved with inspiration from companies that provides/sell a function or result rather than a product. Companies that have those kind of business models are Ricoh (selling per-print), SKF (selling motion), Michelin (selling per-mile) and Rolls Royce (selling power-by-the-hour). This kind of business model require that ABB remains the owner of their products. There are many potentials and risks connected to remaining the owner of products which will be thoroughly evaluated in the SWOT analysis further down.

The proposed way that ABB can sell the function of a LV motor for marine use is through business model 2 which suggest to sell the function mechanical motion per minute (power-by-the-minute). There are a few prerequisites that is needed in order to realize such a model. Firstly, a stable and secure way of monitoring the motors is needed in order to be able to ensure that the function of the motors is always provided. This is suggested to be assured by smart monitoring which ABB already have a solution for. The monitoring of the motors is an advantage for both the customers and for ABB. The advantage for the customers is that ABB always monitoring the motors and can therefore always assure the performance of the motor. For ABB the monitoring of the motors can function as a security of the users, i.e. customer behavior. It has been proven that when customers no longer are the owner of a product, their usage behaviour tends to change. Often towards the worse since “it is not their problem anymore”. The monitoring can directly prove if the motors have been overloaded or used wrongly which will be of great help if disputes regarding why a motor have failed etc. occur.

Secondly, a highly responsive service/maintenance organization is needed to support the kind of PSS that is suggested. When providing a function (or service) ABB have high demands on them to deliver. One of the main reasons for choosing to buy a function instead of an actual product is that the provider is to ensure that the downtime is low to non-existing. Therefore, it will be included in BM 2 to have skilled and highly responsive maintenance personnel. The maintenance/service organization are to retrieve information from the sensors when the motors deviate from its normal performance and then take relevant actions e.g. change bearings, grease or change the motor. An organization like that are expensive to operate and therefore it is of high importance to have robust and long-life products.

Lastly, ABB can favor a design that is built to last. The current ABB low voltage motor is as mentioned earlier designed to be operating for 20 years, but the actual years that the motor is used in average is 5 years. BM 2 is about providing the function of the motor where ABB is responsible for the operation performance of the motor and in such arrangement a long-life motor is desirable. Further, a good quality motor should be easier to maintain and fix if something breaks down.

4.2.2.1 SWOT-analysis BM 2

The potentials and risks connected to BM 2 is thoroughly evaluated in a SWOT analysis, as described in chapter 3.4.1 The results of the analysis are divided in internal and external potentials and risks as seen in figure 20. The content is further described under the figure.

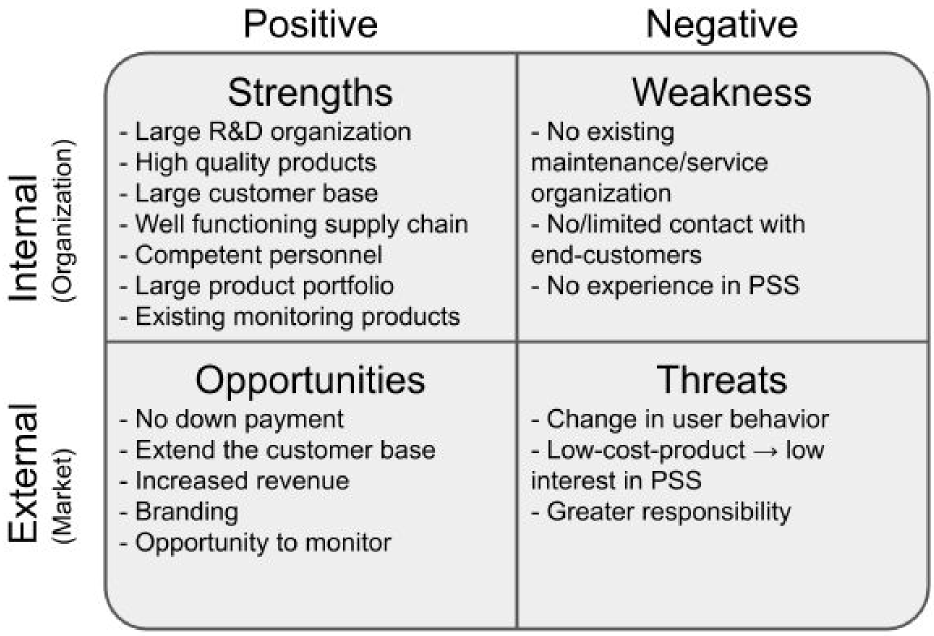

Figure 20. The SWOT-analysis of BM 2 visualized.

Internal - strengths
Many internal strengths of ABB were identified in the SWOT-analysis. Firstly, ABB is a large company with a well-developed R&D and a company that make big investments in developing their business and products to make sure that they are among the best in the market (ABB, 2020b). This facilitates in designing a suiting business model and product, to provide the best motor experience possible from both ABB's and the customer's point of view. As mentioned earlier, one of ABB's competitive advantages is the high quality of their motors. In BM 2, this is an attribute that is very advantageous. A motor with good quality is easier to predict maintenance for and will also require less maintenance, which will decrease the cost of service personnel. Further, the motor can be used for longer periods of time compared to the current situation. This will utilize the potential of the material and products to a larger extent and will reduce the need of new material and components.

Moreover, ABB has a large customer base. To change the business model may not be desirable for all the customers, so to have a large customer base makes it possible to test BM 2 out on a small part of the business. In that way, big investments and organizational changes can be avoided before the business model shows good results. ABB also has a large product portfolio, which means that the business model can be applied in some applications first. Additionally, applications where BM 2 may not suit at all can remain as it works now.

Another strength that was identified in the SWOT-analysis was that ABB has competent personnel with good knowledge in the product and its function. This is important when providing a motor where ABB is responsible for the operating performance.

The last internal strength that was identified was that ABB has an existing solution for smart monitoring of motors and has experience in the field. This will make the transition towards

BM 2 much easier as no new technology needs to be developed, and the knowledge, experience and expertise are already within the company.

Internal - weaknesses
The SWOT analysis highlighted three internal weaknesses for ABB regarding to provide LV motors with BM 2. The first potential weakness is the maintenance/service organization where the capacity might be smaller as compared to what is needed in the PSS model. There are however possibilities to expand their already well functioning organization but as of now they would most likely not be able to handle the increased need. Further, the organization that is existing today work mostly with large and specialized motors and not with the LV motors made in large quantities.

The second internal weakness discussed in the SWOT was the limited availability of information and interaction with end-customers. ABB´s LV motors are almost always integrated as a part in larger systems, e.g. pumps and are therefore often sold to "integrators". In this case integrators means companies that use the motors as an input in their product systems. The integrators are in turn the ones who provide the end-customers with the final product. This is a weakness since ABB are to have a business model that requires close contact with the end-customers. A close collaboration is needed since the motors needs to be monitored and maintained constantly. To be able to implement BM 2 ABB must have a solution where they can stay owners of their products, have close collaboration with the end customers and still be the integrators first choice of motor supplier.

The last internal weakness from the SWOT that ABB have regarding BM 2 is the lack of extensive experience with product service systems. As of today, ABB does not sell a function or a service within the motor business. Many questions, e.g. related to the pricing and other investment costs need to be answered before such a business model can be adopted.

External - opportunities
Several external opportunities were found during the SWOT analysis, one opportunity is that in a PSS model no down payment is needed and the cost for the customers only is based on the amount of usage each month. This means that customers avoid large capital investments which can be spent elsewhere. The absence of large capital investments could also be an enabler for another type of customers different from the ones that ABB have today. That kind of customers, that might be interested in BM 2, is cost conscious customers that are sensitive to larger investments. The opportunity to tap into another customer base is always positive since that would mean more customers which in turn would lead to increased revenues. The PSS model can, if it is well designed, further increase the revenues compared to the traditional way of selling motors. It is a balance act to provide a payment plan that both attract customers and is lucrative for ABB. BM 2 would results in monthly payments instead of one timed down payments which could be preferred since it would create a more steady cash flow.

Another external opportunity that was brought to light during the SWOT analysis was that a product service system can arguably be more environmentally friendly. It is advantageous to have products that have long life and are robust in a PSS. That would mean that the products will be used for a longer time and the need for new raw material is reduced. Providing a more environmentally sustainable product is not only good for the environment but it also is good for the brand ABB.

Lastly, there is an external opportunity in monitoring the motors. The arguments for the opportunity are thoroughly described in the introduction of the PSS model. It can however be summarized as; ABB have the possibilities to ensure that the motors are used correctly and the customers can be assured that the motors meet the performance requirements.

External - threats
The first external threat that was found in the SWOT-analysis was that in some previous cases, as described earlier in 4.2.2, the customer changes their user behavior of the product if the product is not bought. This may increase the workload and wear of the motors, and in that way increase the maintenance and service costs. Another identified threat is that ABBs motor is a low-cost product compared to the the total cost of the motor and its operation. This may lead to a lower interest in a PSS system, as the investment of a motor only is a fraction of the total price anyway.

Finally, the last identified external threat is the high responsibility that comes with BM 2. To provide a service were ABB guarantee the motor to always be up and running, demands high requirements on the products. If the performance cannot reach the expectations of the customers, this can lead to big costs for ABB.

4.2.2.2 Morphological CEBM-box

The design of BM 2 is summarized in the CEBM-box seen in figure 21. Each design option that is included in BM 1 is marked with a red circle. A thorough description of the box and its marked content follows after the figure.

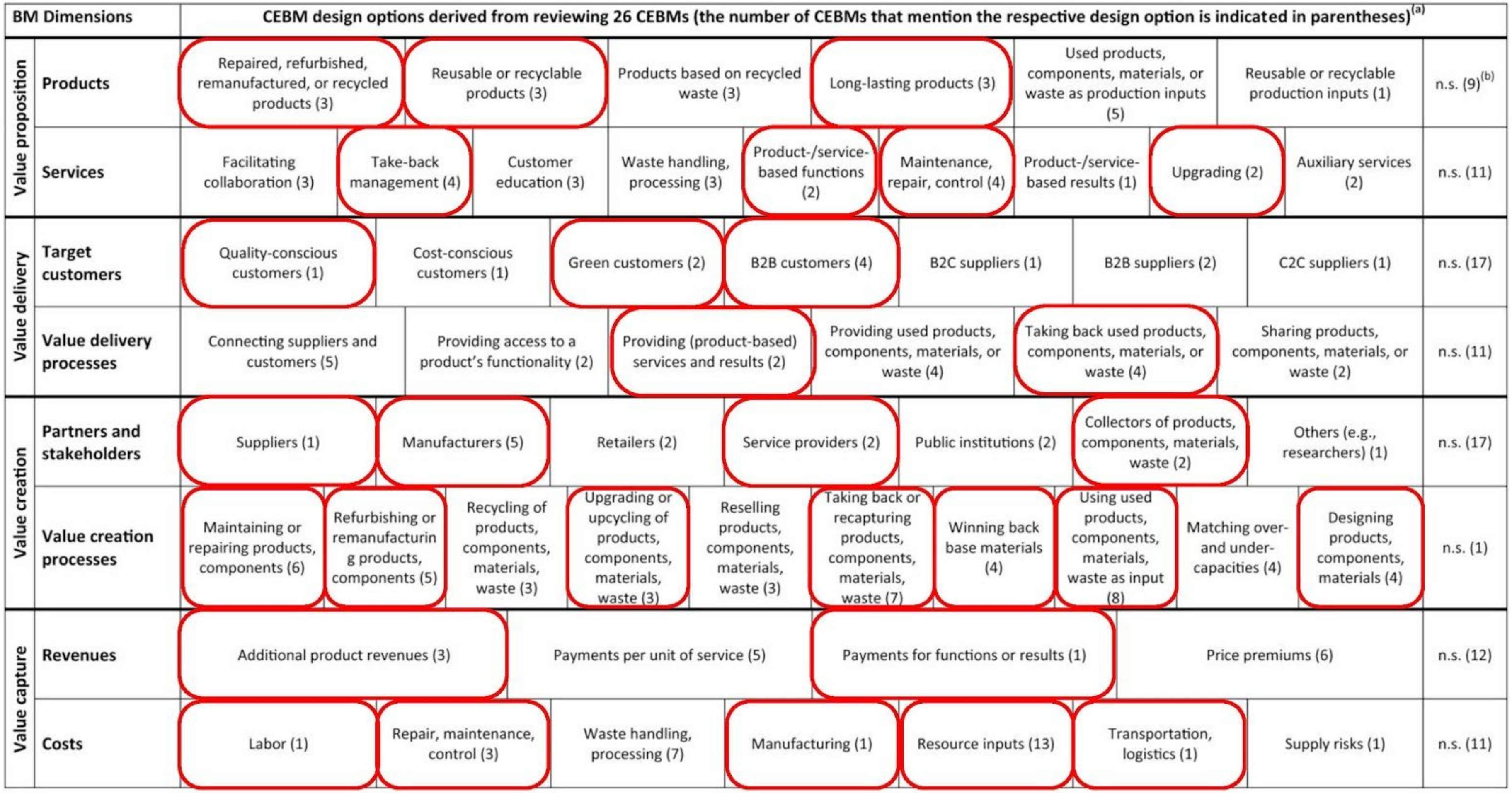

*Figure 21.*The morphological CEBM model for BM1(Lüdecke-Freund et al. 2018). Reprinted with permission.

Value proposition
There are three products for the value propositions in the business model dimensions for BM 2. The first is the repaired, refurbished, remanufactured or recycled products. This product dimension is related to BM 2 since motors will be taken back, sometimes when they do not perform and sometimes when the customers for some reason wants to end the usage of that specific motor. If the motors that are taken back are fully functional there is no reason to discard them, in those cases it makes more sense to clean them and circle them back into the market, i.e. refurbish. The same is if the motors have minor problems that could be easily be repaired. The second dimension that is circled for BM 2 in the value proposition is the reusable or recycled products. As mentioned before, if the motors that are taken back are in good shape and are fully functional there is no reason not to reuse it, hence the circled product dimension. Furthermore, if the motors are worn out they are to be recycled properly so that the material can go into some kind of production stream. The last product dimension that is marked is the long lasting products and the reason for that is that the longer the products are functional the more lucrative the business model become. The customer pays the same amount per usage regardless which motor that are in use and therefore the revenue per motor linearly increase the longer it is used.

Four service value propositions dimensions are connected to BM 2. The first is take-back management which is a part of BM 2 since the functions of the motors are to be provided to the customers. That means that if the sensors indicate that the motor is malfunctioning it is to be repaired or changed hence the take-back service. The second service that is circled is the product-/service- based functions. The reason why that dimension is circled is because the motors are not sold to the customer, the model builds on selling the function of them. The last two services that are marked in the value proposition is maintenance, repair & control and upgrading. Maintenance, repair and control are a part of BM 2 since the motors are to be that by ABB. The control of the motors is the monitoring of them which indicates when maintenance and repairs are needed. The reason why upgrading is a service dimension in BM 2 is because if the motors are to be taken back and refurbished they could be upgraded as well, for instance with new and better monitoring systems.

Value delivery
The first target customers for this business model is the quality-conscious customers. In a product service system, ABB is responsible for the motor to be operating when it should and with the performance that is agreed. Through monitoring, maintenance and service, it is possible to increase the quality of the service. Further, the next target customer is the green customer. Through preventive maintenance and monitoring, the lifetime of the motor can be extended and the resources can be better utilized. For the marine motor, the shipping companies use to have multiple extra motors on the ships just in case of breakdowns or stops. By monitoring the motors, the spare motors may not be needed and these unnecessary motors can be removed. With smart monitoring, the performance of the motor can be analyzed. This assures that the efficiency of the motor can be optimized and unnecessary energy losses can be avoided. The last target customer is the B2B-customers. B2B stands for business to business customers, which means that the customers of the product or service are other businesses rather than individual consumers. The motor will for the most part be sold to other companies and not to individual customers.

For the value delivery process, the first box that is circled is providing (product-based) services and results. This means that ABB will provide the result of a motor powering the water pump, with the service of maintaining the motor and assure that it is operational when it should. The customer will not buy a motor, but the function of the power the motor provides. The last value delivery process is taking back used products, components, materials, or waste. This is a part of BM 2 since the used motors will be taken care of, either through refurbishing and redistribution, or material recovery and recycling if the motors are impossible to repair or reuse. Since BM 2 is based on the service of providing the function of a motor, motors can be reused as long as they perform as specified.

Value creation

The first circled business dimension with partners and stakeholders is suppliers. The suppliers are important to deliver a motor to the customer with the performance and quality that is expected. Further, the suppliers are important for the supply of spare parts, which are necessary to keep the products in the system. The second circled dimension is manufacturers. The manufacturers, which includes ABB, are important in the providing of new motors to the system. Even if the motors within the PSS system are meant to be used for a longer time, there will be a point were old motors are replaced with new motors. The third box that circled is the service provider. This is a very important stakeholder because the whole business depends on the service and maintenance to work and provide a function that the customers are satisfied with. It is necessary that the model gives the customer an advantage of having a service from ABB. The last partners and stakeholders are the collectors of products, components, materials and waste. They are important to capture the values within the old motors and bring it back to the system.

The first value creation process that is circled is maintaining or repairing products and components. This is a main part of the model, as the goal is to extend the operating life of the motor and increase the utilization of the material and energy that is used building a motor. The motor is currently used for only five years until discarded but is designed to last 20 years. By assuring the quality through service and smart maintenance, the use of the motor can be extended. Some of the next business dimensions that are circled are connected to each other in some ways. These are refurbishing or remanufacturing products/components, taking back or recapturing products, components, materials and waste, and winning back base material. All these are important for a business that in some form keeps the ownership of the motor. To keep the products and components operational as long as possible and take care of the existing resources and materials will reduce the need of new inputs to the system. This will extend the value creation of a motor and its components during its life-time. Further, upgrading and upcycling is also important so that the customers motor is up to date. To facilitate these value creation processes, the design of the motor has a big impact. Therefore, the designing products, components and material is circled.

Value capture

There are two business model dimensions in regard to value capture in BM 2; additional product revenues and payments for functions. The additional product revenues are coming from being able to reuse the motors and/or using them for longer periods. As mentioned previously the customers will pay the same amount for usage regardless what motor that is in use. Therefore, if the motors are performing as they should, e.g. working for twenty years, the motor will turn in profits for a longer period than if the motors are discarded every fifth year.

Furthermore, a part of the idea with the PSS model is to reach out to another customer base which would increase the number of customers which in turn would up the revenues. The second business dimension in the value creation process is the payments for functions. This dimension is a part of the value creation since it is the way to charge the customers. The customer will pay for the output power, i.e. the mechanical energy out from the motor, per minute. The cost for using the motor will be so low that the customers are willing to be a part of the business but so high that it after a few years will become highly profitable. There are several cost connected to BM 2 which is a part of the value capture BM dimensions The first one is labor and the reason for that is because many people must be working with various parts in order for the business to be functional. The next cost is the repair, maintenance and control. These costs are both for repairing and monitoring the motors at the customer and for the own manufacturing sites at ABB. The motors still must be manufactured at ABB and therefore there are costs for manufacturing and resource input. The last cost connected to BM 2 is the transportation and logistics dimension. These will be highly resource demanding since many companies are to be served with motors distributed via PSS and therefore it will be costly in regard to logistics.

4.2.2.3 End-of-life potential for BM2

The end-of-life potential of the motor will be higher than the original business model. If ABB are responsible for the maintenance and service and can assure the operating performance, the motor should be able to run for 20 years. This increases the use time span by four which can be an argument for the GWP to decrease with 75% for the material acquisition, component production and the disposal. The continuous maintenance and service would most likely lead to increased transports but this is impossible to know with the gathered data. The use phase will stay the same, given that the efficiency of the motor does not decrease within its expected lifetime.

5. Discussion

The discussion chapter consists of three parts; LCA, CEBM and additional circular measures. In the subheadings, LCA and CEBM, the methods and the results will be discussed and validated. The chapter additional circular measures could be argued to lay outside the scope of this project but it has been chosen to be kept as it could be a good guideline on other circular measures companies can do in order to become more circular.

5.1 LCA

The life cycle assessment that was conducted for ABB on their low voltage marine motor was performed in accordance to what the project manager deemed important for the project. In this section the assumptions made during the study are to be justified according to the set goals of the LCA. The primary reason to conduct the LCA for ABB was to get a quick overview of the current life cycle situation of the motor. The purpose of the study was to identify carbon dioxide hotspots and propose changes in the products life cycle to minimize the impact of those. The total weight of the motor is 665 kg and the material that was a part of the study stood for 97% of the product. Since the results of the study are only to be communicated internally and not be used for benchmarking and external communication the missing 3% are justified to be outside of the study. Furthermore, the importance of the remaining 3% are highly dependent on which impact category that the study is focused on. In the case were the studied impact category is climate change the weight of the product have large effect and therefore the 3% of the motor that is excluded have little impact on the result for a 0,7 ton heavy motor.

In the manufacturing part of the LCA study, both the internal motor production and the external component production, assumptions have been made. Firstly, the component production is based on the data sets that are included in CES EduPack and regarding the effect that the production have is based on the energy mix of which country the parts are manufactured in. It is impossible to say which certain energy mix is used in the specific manufacturing plants since there are no knowledge about those. For instance, some companies buy “green energy” that have little to no effect on the global warming. To strengthen that argument ABB further use more than one OEM for each of the parts for the motor which would make it extremely time consuming if even feasible to collect data on the exact energy mix that have been used to manufacture the components. Furthermore, the transports of the components to the motor assembly plant are based on an average fuel consumption of the vehicles that are transporting the parts. There are more or less environmental aware transportation companies and better or worse vehicles. When it comes to the actual assembly of the motors at ABB in Finland, no data could be acquired which was highly unfortunate. The reason for the lack of data was the current global situation with the outbreak of Covid-19. The manufacturing of components however, showed that the effect on the global warming potential was very small compared to the overall influence on the CO_2 emissions. The use-phase was proved to stand for around 99% of the total impact on the global warming potential. That goes well in line with previous LCA studies of electrical motors have proved before.

The assumptions in the use-phase where set beforehand by ABB and can be questioned, which was done. According to the project manager the numbers of the case presented in chapter 3.2 are based upon information gathered from the business side of ABB, i.e. people who are in contact with the actual customers. However, it cannot be ignored that those assumptions must be very general since there are so many applications for these motors and they are sold to many different customers. If the usage of the motors would be different, just the slightest, it would have great effect on the end-result. For instance, if the ships on which the motors are located where to dock with underwater energy cables which is the case in some ports, the energy that the motor would consume would be of a much better mix (not diesel). The LCA results are valid in regard to what was given by the project management but if it were to be externally communicated a much more thorough analysis must be made regarding the use-phase.

The LCA results were presented during many of the brainstorming sessions that was held during the project. The LCA results was taken into account when discussing potential new business models. During these sessions it was recurring arguments that the impact the motors have during the use-phase are so large in comparison with the manufacturing and material acquisition that it could almost be ignored. There were arguments that the efficiency of the motor is much more important than anything else. These arguments are valid if the only reason for this project was to reduce the CO_2 footprint of the motors but that is not the case. The project is a part of a circular initiative and circularity cover much more than just global warming. A positive result of circular economy is that there could be reduction in CO_2 emissions. When it comes to the motors however the idea with circularity should be to use the resources as much as possible and reduce the need of mining raw material. Regarding the motors this is a complex matter since the use-phase have such a high influence on the environment. New motors have a significant less impact on the environment compared with old motors when looking at GWP. It could therefore be discussed if there are other impact categories that could have been looked into during the LCA.

This paragraph will discuss the project from a academia point of view in order to provide information regarding what others could expect from a similar project, for instance potential benefits and pitfalls. This project has been a success, taken the time limit into account, when identifying environmental hotspots in a products life-cycle. However, it is, once again, highly important to underline that the results of this study only can be used internally. A full ISO-compliant LCA requires much more resources and time to be performed but in a case like this the screening LCA is good enough. When suggesting further work after a project like this it is recommended to propose more thorough evaluations where the highest hotspots where found in order to propose actions. When performing a LCA with the purpose to find CO_2 hotspots it is of great importance to early in the project retrieve good and relevant data. This was one of the biggest challenges in this project.

5.2 Circular business models

The two suggestions of CEBM, the remanufacturing model and the PSS model, were a result of an extensive search of what other companies are doing regarding circular economy, interviews and a variety of brainstorming sessions. The work put down in the analysis of other companies´ strategies regarding circular business models was extensive and the resulting suggestions would most likely not have been affected if more time and resources were used. The interviews and brainstorming sessions could on the other hand, if performed in another way, affected how the two suggestions were designed. The interviews and brainstorming sessions were held with various (relevant) stakeholders, as mentioned in chapter 3.1, but what would have happened if other people were interviewed? The people that were part of the interviews and brainstormings gave good insight and had a large role in the results but what if people, say from companies that have functioning CEBM up and running where interviewed? They would most likely not be interested to share their knowledge but the message that is aimed to reveal is obvious, *interviews and brainstorming sessions with other people would most likely have changed the result.*

The inputs to the SWOT analysis were collected from ABB and assessed as unbiased as possible. There is however a risk that the data collected are biased in its own. That should be taken into account when going through the SWOT results. The box for deciding upon the design of the CEBM is based upon 26 real life CEBM. It is a good compilation and it is a credible tool. However, the paper about the design box, event though it was published in 2019, could have missed new and lucrative CEBM that could provide relevant input in the design box. The uncertainties in the methods were the reason why both the SWOT and the design box were used in order to get the resulting two CEBM, BM 1 and BM 2, as good as possible.

It was decided relatively early on, in collaboration with the project management, that the two models BM 1 and BM 2 were to be further developed. At that point in the project work when it was decided to focus on the two models it seemed like the right thing to do. However, it is worth to discuss whether another CEBM could have been a valid candidate to become a way for ABB to provide their LV marine motors. In this case it was found that, since ABB is the manufacturer of the product, the two models were the most suitable. For instance, the cascading CEBM such as ebay and blocket is not so relevant in this case because ABB is the manufacturer of the main product (it would have been more suitable if the case where a financial company that provided the motors to the customers).

There are several economical and customer aspects that are to be discussed regarding BM 1 and BM 2. There were not enough sufficient data provided regarding what customers really want and how they are using the products today. It is therefore hard or even impossible in this stage (with the current knowledge) to come up with pricing and quantitative economic results. For instance, it would be of high interest for ABB if this project ended up with a suggestion on how much the incentives for the remanufacturing model should be or how much the customers were willing to pay for the motor-usage in the PSS model but that is not the case. Furthermore, the motors are relatively low cost products in the aspect that their acquisition cost is around one percentage of the total cost for using the products over its entire lifetime. That could be a disabler for both the suggested business models. That is one of the reasons for why it would be interesting if customers could be assessed further. If data could be collected regarding what the customers say to be their number one priority when it comes to the product evaluated in this project, the LV marine motor, more arguments for the CEBM could be provided. For instance, if the customers found reliability to be their number one priority, then the PSS system could be something that the customers would be interested in. If the number one priority is to reduce down payments the remanufacturing model could be of higher interest. As mentioned it is at this moment impossible to know but if facts about the customers needs and wants were provided, one or even both the suggested CEBM could be approved to have potentials or be discarded.

There where one aspect throughout the building of the suggested CEBM that proved to be tough to come up with solutions around. That is the fact that the motor is a part of a larger product system and it would therefore be troublesome to handle the ownership for the motor. One example is in the PSS model, how would the fact that the motor is integrated into another companies product be affected if ABB remained owner of the motor. Would integrators, i.e. the builders of the complete product systems, be interested in using motors that they are not the owner of? The common case is that the integrators buy motors from ABB and then they sell them as a part of their machines or systems with a markup. There were suggestions, that were brought up during a brainstorming session, about having a financial company to be the owner of the product but that would not change the dilemma with the motors being a part of a larger system.

During one of the brainstorming sessions with a senior person at ABB the remanufacturing model was discussed. It was brought to light during the session that ABB had done testing with repairing LV motors and it had been proved that when repairing motors with insulation problems (a common failure mode) the motors lost around 1% in efficiency. As presented in the LCA part of the study, the use-phase stands for 99% of the total GWP for the motor assessed in this project. The efficiency have great impact on the environment and it is therefore important to discuss whether it is worth to remanufacture motors with the kinds of failures that lower the efficiency. In those cases it would perhaps be better to strip the motors for parts that can be reused and ensure proper recycling of the parts that would decrease the efficiency if repaired. This kind of problem is a dilemma since the refurbishment of an old products could heavily impact the environment but the manufacturing of new products have other impacts such as on scarce resources. It is therefore important to back-up decisions regarding if remanufacturing is worth doing with facts regarding the environmental impact.

The end-of-life potential is a result that Eco audit, the tool used for LCA in the software CES EduPack, provides with the given data on what is made with the components in the EoL-phase. It was not much work to get the EoL potential for BM 1 once the LCA had been made on the current situation with the LV marine motor. The recycled content was replaced with remanufacturing content instead. The assumption regarding how much of the components that got remanufactured was an assumption based upon the fact that not all components could possibly be circled back into the market. Some components would most likely be broken beyond repair. It can be argued that the content of every remanufactured component, 90%, is a high remanufacturing content. It basically means that 90% of the motor components (the housing, wires and core steel) is going back on the market. The assumption is backed up with the facts of the case of the LV marine motors, for instance, the fact that they are built to last for 20 years but are discarded after 5. That means that the motors should be able to only be refurbished, e.g. cleaned and repainted, three times and then be put back on the market with 100% of the original content.

From an academic point of view, this workflow can be used as an guideline for similar work in this subject. The selected methods has complimented each other in a good way since the SWOT analysis highlights the strengths and weaknesses while the morphological box analysis captures how to design CEBMs. It is important to have in mind that there are other analysis methods that can be used that could end up with other results. The results of this project have however been proven to be successful since the project management is satisfied and there are indications that the CEBM will be further evaluated. The methods used in this project have shown promising result but it is of high importance to keep in mind that this is one specific product for one specific company, a case study. It could be that these methods are not suitable for other, similar, projects.

5.3 Additional circular measures

During the literature search of circular economy and when assessing what companies are doing in a circular matter today, several practises where discovered. Some of these did not fit into the two proposed BM but they are worth mentioning as they could be applied anyway. The reason why they are brought up is that they are relatively easy to apply and it would be highly beneficial for resource usage overall if ABB and other companies were to be more circular. The first thing is to reduce the use of virgin material and look into having more recycled content in products. Secondly, if possible the best way to save resources and energy which leads to less impact on the environment is to reuse whole parts as much as possible. Lastly, the practice that Maersk are using with product passports is something that as many companies as possible should apply in their own products. There are so much material that goes into recycling that becomes contaminated. If the products were more properly recycled the usage of virgin material could be lowered significantly.

6. Conclusion and recommendations

This chapter will consists of a conclusion where the two research questions will be addressed directly regarding the results of this study. It will furthermore take up recommendations for future work regarding the objectives of the project.

RQ1: What are the CO_2 hotspots along ABB's LV marine motors life cycle? How to reduce the environmental impact of these hotspots?

The results of the life cycle assessment pointed out, with high possibility, that the part of the life cycle of the LV marine motors that have the highest impact on the CO_2 footprint is the use-phase. There are a few ways for the project owners to reduce the impact in the use-phase and that is to increase the efficiency of the motors and request that the customers choose the motors with the highest efficiency. That however, is a cost issue that the customers are to evaluate. Since the use-phase is somewhat out of reach it is more interesting to look upon the phases that ABB do have higher possibilities to affect. The material acquisition phase is by far the phase with the highest impact after the use-phase. Recommendations for reducing the CO_2 footprint in this phase are presented in the report and can be concluded to; using the motors longer and/or remanufacturing the motors in order to minimize the need for virgin material. The reduction in the material acquisition-phase is definitely something that would be achieved if one of the two CEBM where to be used. Circular economy is based upon using products and resources for as long as possible which most certainly means to decrease the need for virgin material.

RQ2: Which business models have potentials for ABB in order to enable the providing of LV marine motors in a more circular way and thereby reduce the environmental impact?

During the execution of this project there where two circular economy business models that was deemed to be worth evaluating further. The two CEMB, the remanufacturing model and the PSS model, are still in the early stage of conceptualizing but so far they are still valid candidates to provide the LV marine motors in a more circular and environmental friendly way. The suggested models have been presented to a variety of stakeholders within ABB and they have yet to be shut down. It can therefore be said that BM 1 and BM 2 have potentials to be a new way for ABB to provide their customers with LV marine motors in a more circular way.

Conclusion points

- The findings in this project have relatively high internal validity since it has been an iterative project which has included a large variety of stakeholders that represent different parts of ABB's organization.
- The findings in the project have relatively low external validity which needs to be taken into account if using it in other contexts.
- This report could be used as a guide line for others in how to evaluate and come to a conclusion for how companies or products can work/be used in a more circular manner.

Final conclusion

During the work with this project it was found that there are limited literature regarding how companies could evaluate their products and business models to become more circular and decrease their impact on the GWP. That said, we need to continue our efforts as existing methods are not always easy to use and companies are not always willing to make the effort to use these methods. This study has tried to provide an answer to the question on how to move towards a more circular business model and at the same time decrease the GWP. It is too early to say whether the work procedure was successful. At this stage however, the authors of this report are confident that the proposed work procedure described in the study have potential to be fruitful.

Recommendation for future work

The following bullet list states the recommendation for future work related to the project.

- The motion division at ABB Corporate Research in Västerås has recently invested in a LCA software which is a step in the right direction in order to work in a more structured and sustainable way. ABB should consider how to do LCA work more efficient and one way to do it is to integrate LCA more throughout the organization which would make the data collection step more efficient for the LCA practitioners.
- Due to the unfortunate outbreak of Covid-19 there was no possibility to access relevant data from the actual motor production on Vaasa, Finland. That is something that should be done in order to get information about the environmental footprint the motor production is responsible for. The information regarding the footprint should be assessed and evaluated to be able to suggest new procedures to reduce the environmental footprint.
- Further evaluate the two suggested business models. It can be done by looking into the following; what are the customers number one priority when it comes to LV marine motors and what are the customers willing to pay for that product? When that is known economical plans for the business models can be developed and assessed.

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Appendix A

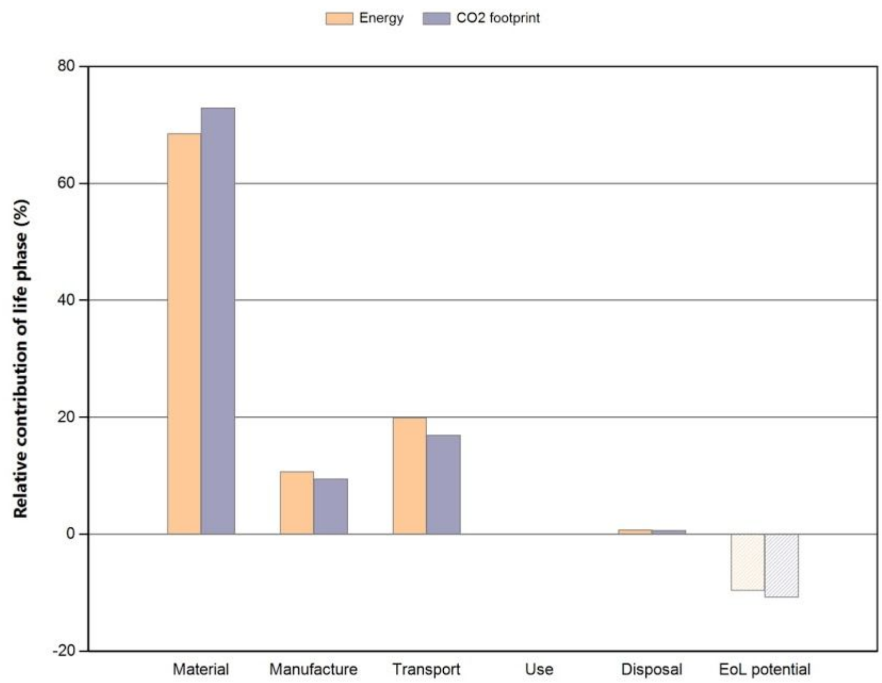
Detailed report from CES-edupack regarding the electrical steel for the current situation

CES 2019 EDUPACK

Eco Audit Report

Product name	Electrical steel to LVMotor correct
Country of use	Norway
Product life (years)	5

Summary:

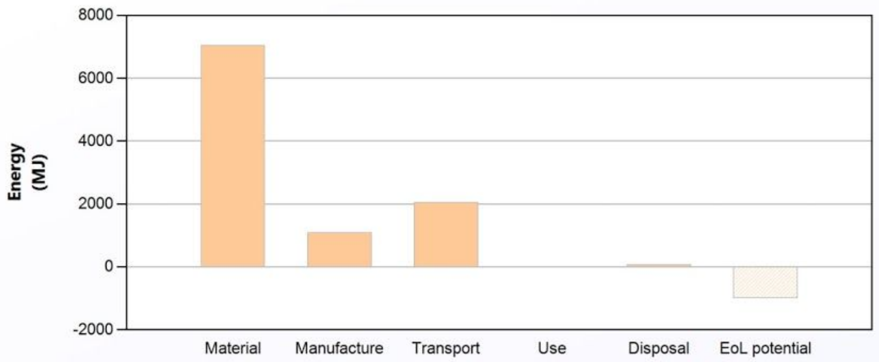


Energy details   CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	7,05e+03	68,5	637	73,0
Manufacture	1,11e+03	10,7	82,9	9,5
Transport	2,05e+03	19,9	148	16,9
Use	0	0,0	0	0,0
Disposal	79,1	0,8	5,54	0,6
Total (for first life)	**1,03e+04**	**100**	**873**	**100**
End of life potential	-987		-94,2	

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 5 year product life):	2,06e+03

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Electrical steel/Core steel	Soft magnetic alloy, 1 Si-Fe, free machining	Virgin (0%)	2,6e+02	1	2,9e+02	7,1e+03	100,0
Total				**1**	**2,9e+02**	**7,1e+03**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Electrical steel/Core steel	Roll forming	-	2,9e+02 kg	1,1e+03	99,2
Electrical steel/Core steel	Cutting and trimming	10	29 kg	8,8	0,8
Total				**1,1e+03**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Ekaterineburg to Vaasa	Rail freight	2,2e+04	2,1e+03	100,0
Total		**2,2e+04**	**2,1e+03**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Electrical steel/Core steel	2,6e+02	2,1e+03	100,0
Total	**2,6e+02**	**2,1e+03**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	Energy (MJ)	%
Electrical steel/Core steel	Recycle	20,0	79	100,0
Total			**79**	**100**

EoL potential:

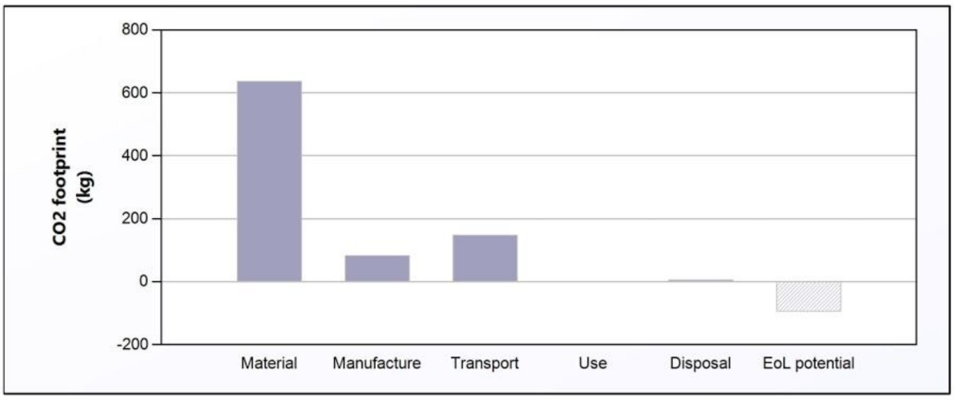
Component	End of life option	% recovered	Energy (MJ)	%
Electrical steel/Core steel	Recycle	20,0	-9,9e+02	100,0
Total			**-9,9e+02**	**100**

Notes:

Summary

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 5 year product life):	175

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Electrical steel/Core steel	Soft magnetic alloy, 1 Si-Fe, free machining	Virgin (0%)	2,6e+02	1	2,9e+02	6,4e+02	100,0
Total				1	2,9e+02	6,4e+02	100

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO2 footprint (kg)	%
Electrical steel/Core steel	Roll forming	-	2,9e+02 kg	82	99,2
Electrical steel/Core steel	Cutting and trimming	10	29 kg	0,67	0,8
Total				83	100

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Ekaterineburg to Vaasa	Rail freight	2,2e+04	1,5e+02	100,0
Total		**2,2e+04**	**1,5e+02**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Electrical steel/Core steel	2,6e+02	1,5e+02	100,0
Total	**2,6e+02**	**1,5e+02**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	CO2 footprint (kg)	%
Electrical steel/Core steel	Recycle	20,0	5,5	100,0
Total			**5,5**	**100**

EoL potential:

Component	End of life option	% recovered	CO2 footprint (kg)	%
Electrical steel/Core steel	Recycle	20,0	-94	100,0
Total			**-94**	**100**

Notes:

Summary

Appendix B

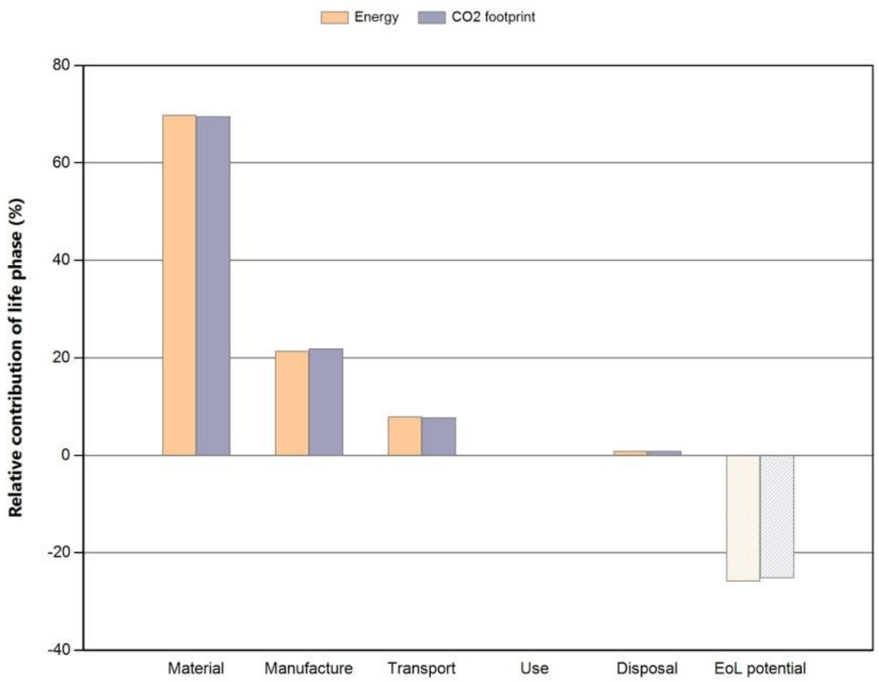
Detailed report from CES-edupack regarding the cast iron for the current situation

CES 2019 EDUPACK

Eco Audit Report

Product name	Cast iron housing to LVMotor
Country of use	Norway
Product life (years)	5

Summary:

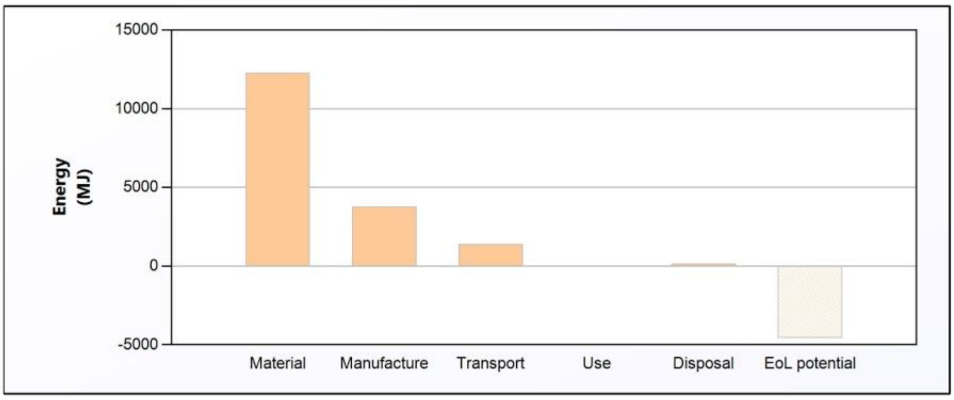


Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	1,23e+04	69,8	899	69,5
Manufacture	3,77e+03	21,4	283	21,9
Transport	1,39e+03	7,9	100	7,8
Use	0	0,0	0	0,0
Disposal	157	0,9	11	0,8
Total (for first life)	**1,76e+04**	**100**	**1,29e+03**	**100**
End of life potential	-4,56e+03		-325	

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 5 year product life):	3,52e+03

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Housing	Cast iron, high silicon, BS grade Si 10	Virgin (0%)	3,5e+02	1	3,5e+02	1,2e+04	100,0
Total				1	3,5e+02	1,2e+04	100

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Housing	Casting	-	3,5e+02 kg	3,8e+03	100,0
Total				3,8e+03	100

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Ocean freight from Beijing to Vaasa	Ocean freight	2,2e+04	1,4e+03	100,0
Total		**2,2e+04**	**1,4e+03**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Housing	3,5e+02	1,4e+03	100,0
Total	**3,5e+02**	**1,4e+03**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	Energy (MJ)	%
Housing	Recycle	50,0	1,6e+02	100,0
Total			**1,6e+02**	**100**

EoL potential:

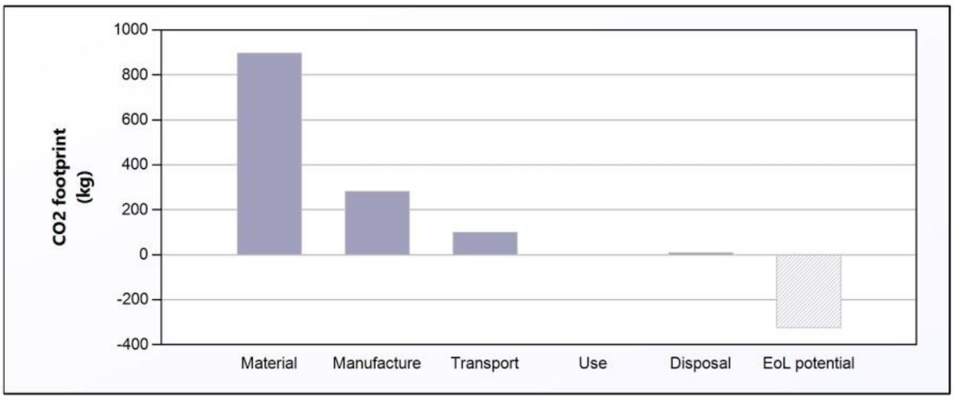
Component	End of life option	% recovered	Energy (MJ)	%
Housing	Recycle	50,0	-4,6e+03	100,0
Total			**-4,6e+03**	**100**

Notes:

Summary

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 5 year product life):	259

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Housing	Cast iron, high silicon, BS grade Si 10	Virgin (0%)	3,5e+02	1	3,5e+02	9e+02	100,0
Total				**1**	**3,5e+02**	**9e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO2 footprint (kg)	%
Housing	Casting	-	3,5e+02 kg	2,8e+02	100,0
Total				**2,8e+02**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Ocean freight from Beijing to Vaasa	Ocean freight	2,2e+04	1e+02	100,0
Total		**2,2e+04**	**1e+02**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Housing	3,5e+02	1e+02	100,0
Total	**3,5e+02**	**1e+02**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	CO2 footprint (kg)	%
Housing	Recycle	50,0	11	100,0
Total			**11**	**100**

EoL potential:

Component	End of life option	% recovered	CO2 footprint (kg)	%
Housing	Recycle	50,0	-3,2e+02	100,0
Total			**-3,2e+02**	**100**

Notes:

Summary

Appendix C

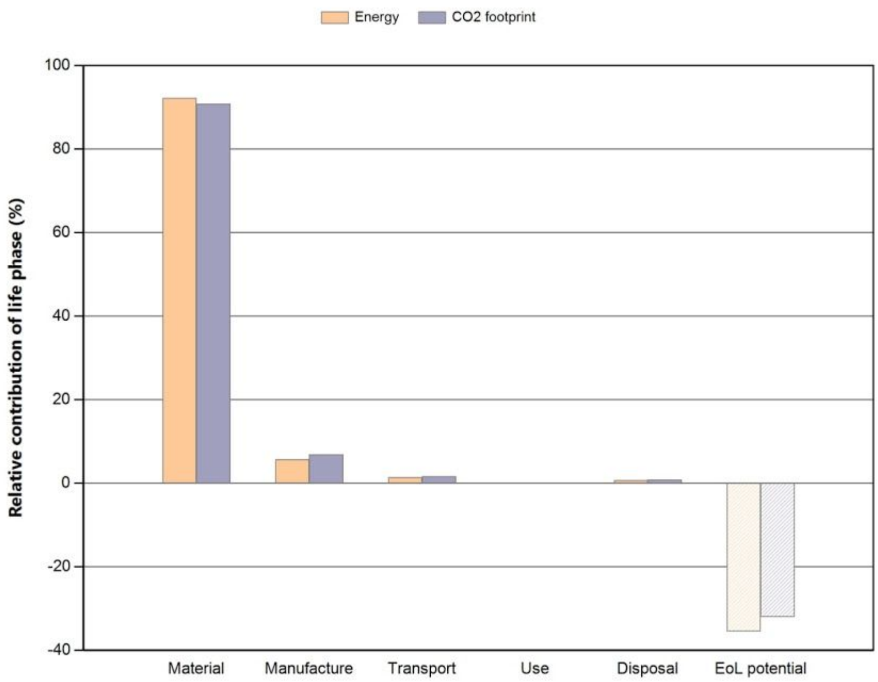
Detailed report from CES-edupack regarding the copper for the current situation

GRANTA CES 2019 EDUPACK

Eco Audit Report

Product name	Coppper wire to LVMotor
Country of use	Norway
Product life (years)	5

Summary:



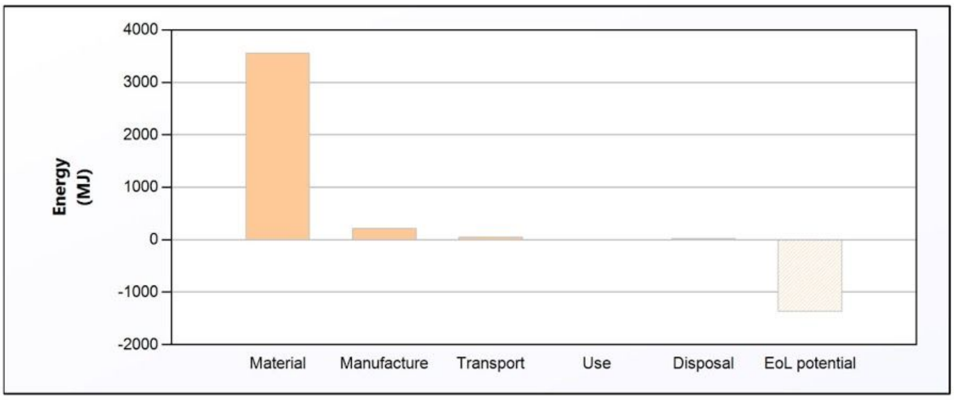
Energy details   CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	3,56e+03	92,2	219	90,7
Manufacture	221	5,7	16,6	6,9
Transport	52,2	1,4	3,76	1,6
Use	0	0,0	0	0,0
Disposal	27,6	0,7	1,93	0,8
Total (for first life)	**3,86e+03**	**100**	**241**	**100**
End of life potential	-1,37e+03		-77	

Coppper wire to LVMotor.prd   NOTE: Differences of less than 20% are not usually significant. See notes on precision and data sources.   Page 1 / 5 den 29 april 2020

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 5 year product life):	773

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Copper wiring	Copper, C10100, soft (electrolytic tough-pitch h.c. copper)	2,0%	61	1	61	3,6e+03	100,0
Total				**1**	**61**	**3,6e+03**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Copper wiring	Wire drawing	-	61 kg	2,2e+02	100,0
Total				**2,2e+02**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Truck from mine to wire manifacturer and from port in Helsingfors to Vaasa	40 tonne (6 axle) truck	8,3e+02	42	79,8
Canal freight from Sthlm to Helsingfors	River/canal freight	4,3e+02	11	20,2
Total		**1,3e+03**	**52**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Copper wiring	61	52	100,0
Total	**61**	**52**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	Energy (MJ)	%
Copper wiring	Recycle	50,0	28	100,0
Total			**28**	**100**

EoL potential:

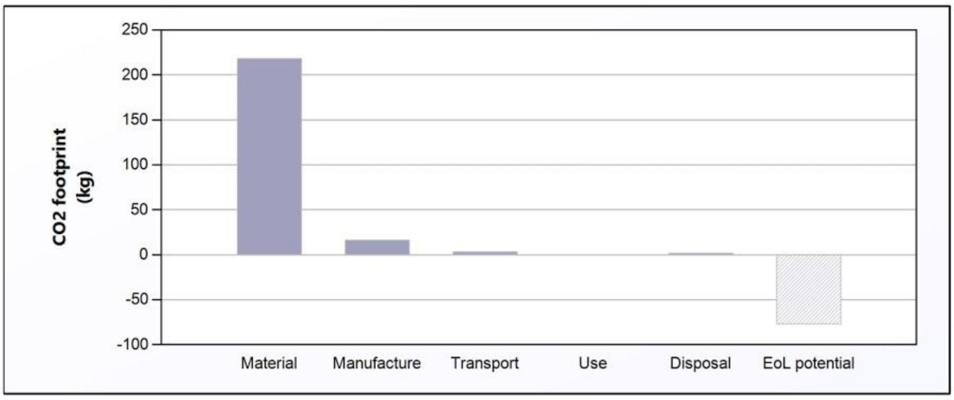
Component	End of life option	% recovered	Energy (MJ)	%
Copper wiring	Recycle	50,0	-1,4e+03	100,0
Total			**-1,4e+03**	**100**

Notes:

Summary

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 5 year product life):	48,2

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Copper wiring	Copper, C10100, soft (electrolytic tough-pitch h.c. copper)	2,0%	61	1	61	2,2e+02	100,0
Total				**1**	**61**	**2,2e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO2 footprint (kg)	%
Copper wiring	Wire drawing	-	61 kg	17	100,0
Total				**17**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Truck from mine to wire manifacturer and from port in Helsingfors to Vaasa	40 tonne (6 axle) truck	8,3e+02	3	79,8
Canal freight from Sthlm to Helsingfors	River/canal freight	4,3e+02	0,76	20,2
Total		**1,3e+03**	**3,8**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Copper wiring	61	3,8	100,0
Total	**61**	**3,8**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	CO2 footprint (kg)	%
Copper wiring	Recycle	50,0	1,9	100,0
Total			**1,9**	**100**

EoL potential:

Component	End of life option	% recovered	CO2 footprint (kg)	%
Copper wiring	Recycle	50,0	-77	100,0
Total			**-77**	**100**

Notes:

Summary

Appendix D

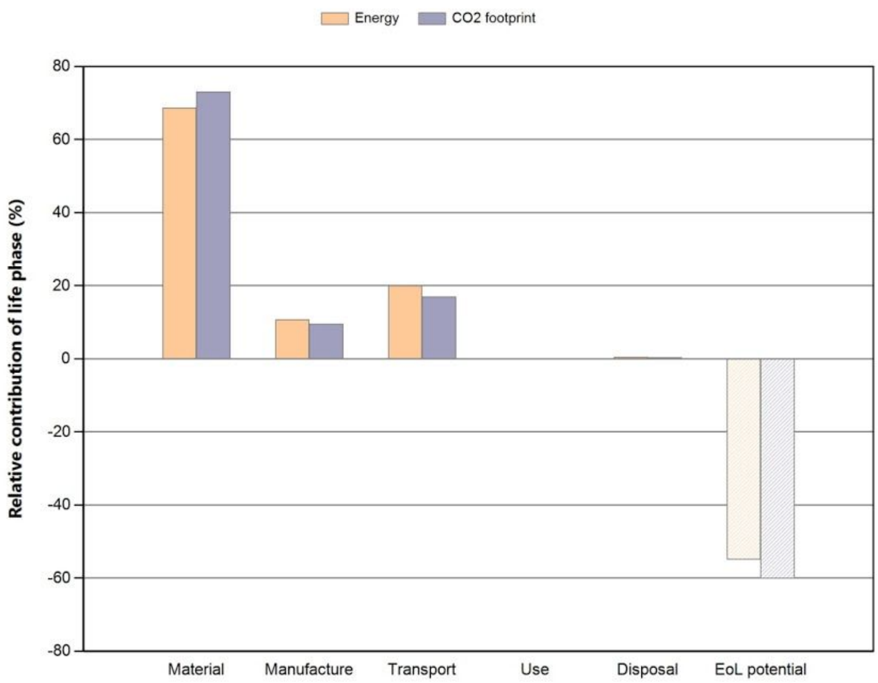
Detailed report from CES-edupack regarding the electrical steel for the remanufacturing model

CES 2019 EDUPACK

Eco Audit Report

Product name	Electrical steel to LVMotor
Country of use	Norway
Product life (years)	5

Summary:



Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	7,05e+03	68,7	637	73,1
Manufacture	1,11e+03	10,8	82,9	9,5
Transport	2,05e+03	20,0	148	16,9
Use	0	0,0	0	0,0
Disposal	52,7	0,5	3,69	0,4
Total (for first life)	**1,03e+04**	**100**	**872**	**100**
End of life potential	-5,63e+03		-524	

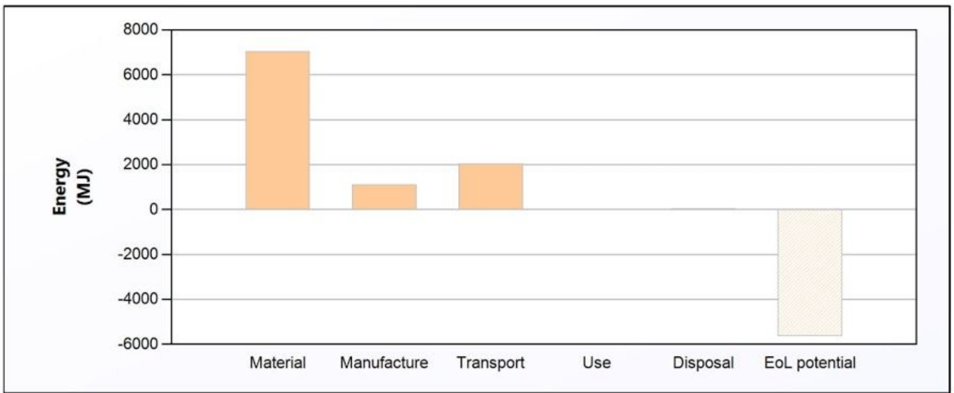
Electrical steel to LVMotor V2.prd NOTE: Differences of less than 20% are not usually significant. See notes on precision and data sources. Page 1 / 5 den 29 april 2020

CES 2019 EDUPACK

Eco Audit Report

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 5 year product life):	2,05e+03

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Electrical steel/Core steel	Soft magnetic alloy, 1 Si-Fe, free machining	Virgin (0%)	2,6e+02	1	2,9e+02	7,1e+03	100,0
Total				**1**	**2,9e+02**	**7,1e+03**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Electrical steel/Core steel	Roll forming	-	2,9e+02 kg	1,1e+03	99,2
Electrical steel/Core steel	Cutting and trimming	10	29 kg	8,8	0,8
Total				**1,1e+03**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Ekaterineburg to Vaasa	Rail freight	2,2e+04	2,1e+03	100,0
Total		**2,2e+04**	**2,1e+03**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Electrical steel/Core steel	2,6e+02	2,1e+03	100,0
Total	**2,6e+02**	**2,1e+03**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	Energy (MJ)	%
Electrical steel/Core steel	Re-manufacture	90,0	53	100,0
Total			**53**	**100**

EoL potential:

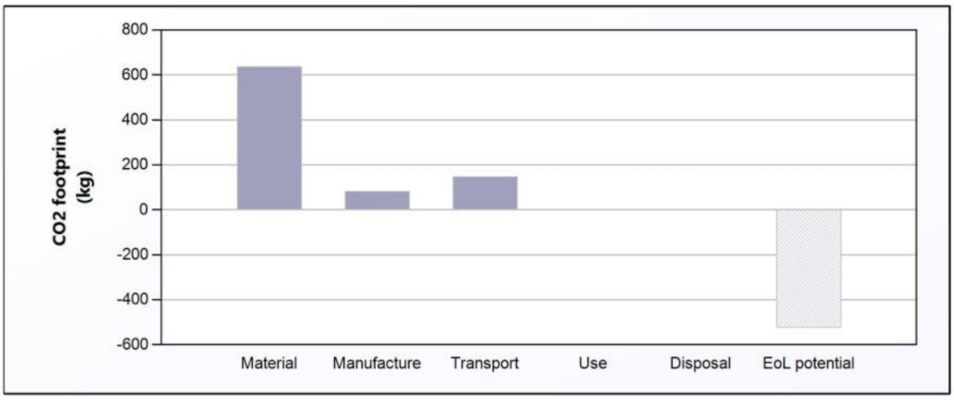
Component	End of life option	% recovered	Energy (MJ)	%
Electrical steel/Core steel	Re-manufacture	90,0	-5,6e+03	100,0
Total			**-5,6e+03**	**100**

Notes:

Summary

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 5 year product life):	174

Detailed breakdown of individual life phases

Material:

Summary

Component	**Material**	**Recycled content* (%)**	**Part mass (kg)**	**Qty.**	**Total mass processed** (kg)**	**CO2 footprint (kg)**	**%**
Electrical steel/Core steel	Soft magnetic alloy, 1 Si-Fe, free machining	Virgin (0%)	2,6e+02	1	2,9e+02	6,4e+02	100,0
Total				**1**	**2,9e+02**	**6,4e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	**Process**	**% Removed**	**Amount processed**	**CO2 footprint (kg)**	**%**
Electrical steel/Core steel	Roll forming	-	2,9e+02 kg	82	99,2
Electrical steel/Core steel	Cutting and trimming	10	29 kg	0,67	0,8
Total				**83**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Ekaterineburg to Vaasa	Rail freight	2,2e+04	1,5e+02	100,0
Total		**2,2e+04**	**1,5e+02**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Electrical steel/Core steel	2,6e+02	1,5e+02	100,0
Total	**2,6e+02**	**1,5e+02**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	CO2 footprint (kg)	%
Electrical steel/Core steel	Re-manufacture	90,0	3,7	100,0
Total			**3,7**	**100**

EoL potential:

Component	End of life option	% recovered	CO2 footprint (kg)	%
Electrical steel/Core steel	Re-manufacture	90,0	-5,2e+02	100,0
Total			**-5,2e+02**	**100**

Notes:

Summary

Appendix E

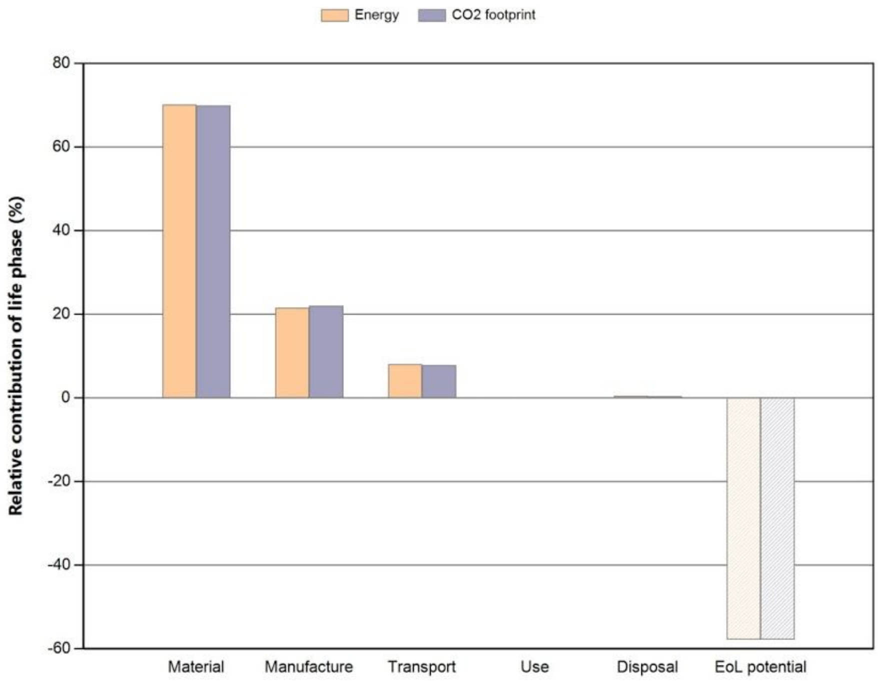
Detailed report from CES-edupack regarding the cast iron for the remanufacturing model

CES 2019 EDUPACK

Eco Audit Report

Product name	Cast iron housing to LVMotor remanufactured 90%
Country of use	Norway
Product life (years)	5

Summary:



Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	1,23e+04	70,1	899	69,9
Manufacture	3,77e+03	21,5	283	22,0
Transport	1,39e+03	8,0	100	7,8
Use	0	0,0	0	0,0
Disposal	69,6	0,4	4,87	0,4
Total (for first life)	**1,75e+04**	**100**	**1,29e+03**	**100**
End of life potential	-1,01e+04		-743	

Cast iron housing to LVMotor remanufactured 90.prd

NOTE: Differences of less than 20% are not usually significant.
See notes on precision and data sources.

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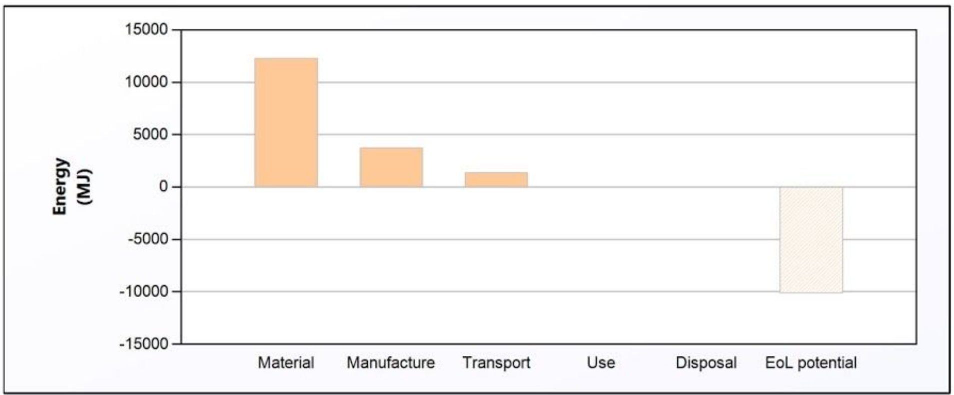
CES 2019 EDUPACK

Eco Audit Report

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 5 year product life):	3,5e+03

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Housing	Cast iron, high silicon, BS grade Si 10	Virgin (0%)	3,5e+02	1	3,5e+02	1,2e+04	100,0
Total				**1**	**3,5e+02**	**1,2e+04**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Housing	Casting	-	3,5e+02 kg	3,8e+03	100,0
Total				**3,8e+03**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Ocean freight from Beijing to Vaasa	Ocean freight	2,2e+04	1,4e+03	100,0
Total		**2,2e+04**	**1,4e+03**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Housing	3,5e+02	1,4e+03	100,0
Total	**3,5e+02**	**1,4e+03**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	Energy (MJ)	%
Housing	Re-manufacture	90,0	70	100,0
Total			**70**	**100**

EoL potential:

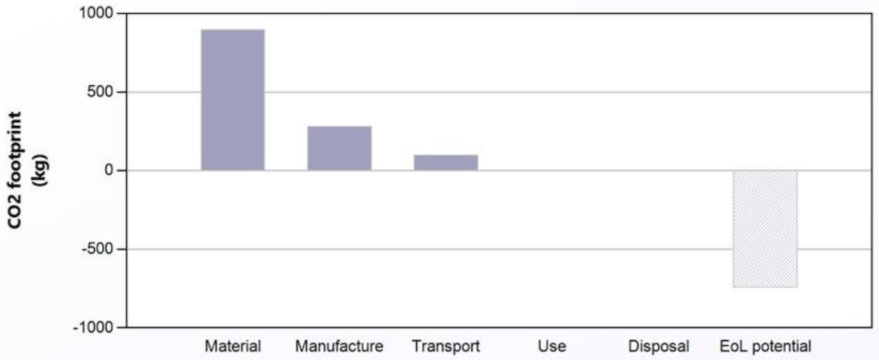
Component	End of life option	% recovered	Energy (MJ)	%
Housing	Re-manufacture	90,0	-1e+04	100,0
Total			**-1e+04**	**100**

Notes:

Summary

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 5 year product life):	257

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Housing	Cast iron, high silicon, BS grade Si 10	Virgin (0%)	3,5e+02	1	3,5e+02	9e+02	100,0
Total				1	3,5e+02	9e+02	100

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO2 footprint (kg)	%
Housing	Casting	-	3,5e+02 kg	2,8e+02	100,0
Total				2,8e+02	100

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Ocean freight from Beijing to Vaasa	Ocean freight	2,2e+04	1e+02	100,0
Total		**2,2e+04**	**1e+02**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Housing	3,5e+02	1e+02	100,0
Total	**3,5e+02**	**1e+02**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	CO2 footprint (kg)	%
Housing	Re-manufacture	90,0	4,9	100,0
Total			**4,9**	**100**

EoL potential:

Component	End of life option	% recovered	CO2 footprint (kg)	%
Housing	Re-manufacture	90,0	-7,4e+02	100,0
Total			**-7,4e+02**	**100**

Notes:

Summary

Appendix F

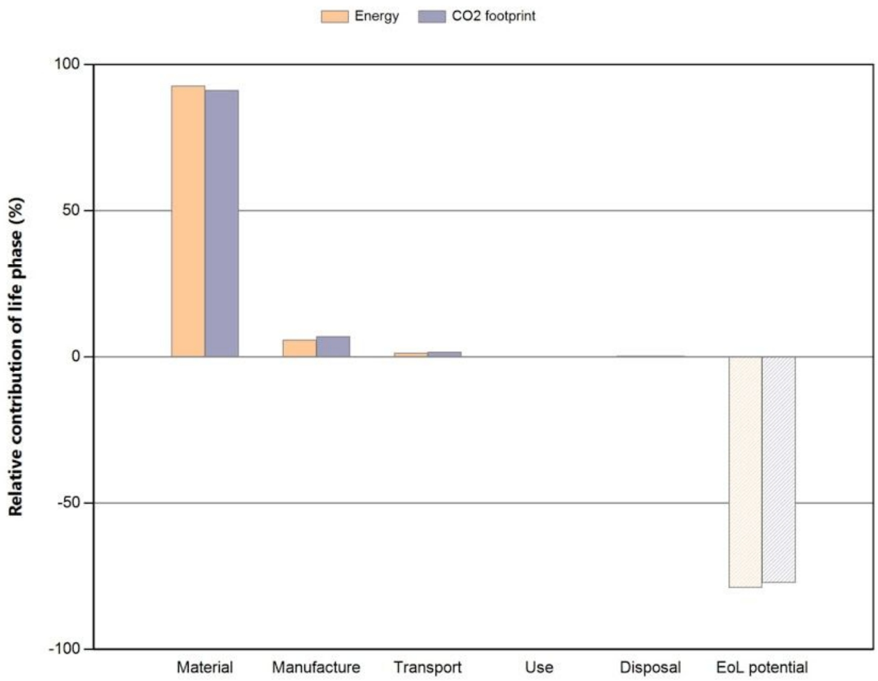
Detailed report from CES-edupack regarding the copper for the remanufacturing model

CES 2019 EDUPACK

Eco Audit Report

Product name	Coppper wire to LVMotor
Country of use	Norway
Product life (years)	5

Summary:



Energy details   CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	3,56e+03	92,6	219	91,2
Manufacture	221	5,8	16,6	6,9
Transport	52,2	1,4	3,76	1,6
Use	0	0,0	0	0,0
Disposal	12,3	0,3	0,86	0,4
Total (for first life)	**3,85e+03**	**100**	**240**	**100**
End of life potential	-3,04e+03		-185	

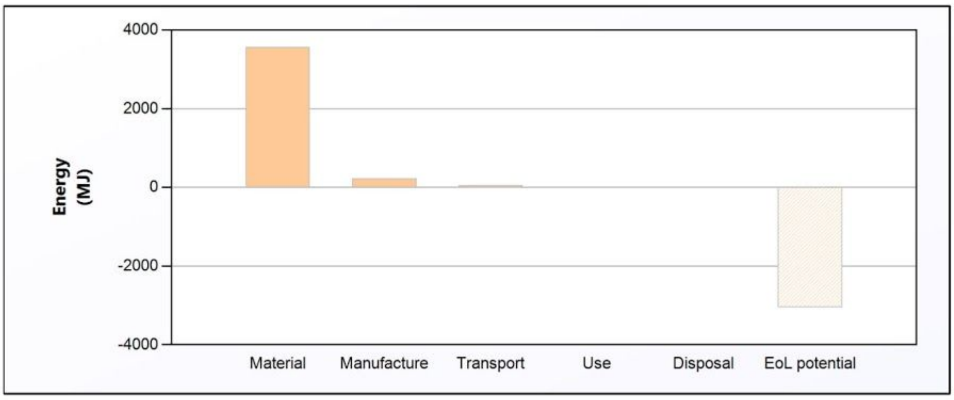
Coppper wire to LVMotor V2.prd   NOTE: Differences of less than 20% are not usually significant. See notes on precision and data sources.   Page 1 / 5   den 29 april 2020

CES 2019 EDUPACK

Eco Audit Report

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 5 year product life):	770

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Copper wiring	Copper, C10100, soft (electrolytic tough-pitch h.c. copper)	2,0%	61	1	61	3,6e+03	100,0
Total				1	61	3,6e+03	100

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Copper wiring	Wire drawing	-	61 kg	2,2e+02	100,0
Total				2,2e+02	100

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Truck from mine to wire manifacturer and from port in Helsingfors to Vaasa	40 tonne (6 axle) truck	8,3e+02	42	79,8
Canal freight from Sthlm to Helsingfors	River/canal freight	4,3e+02	11	20,2
Total		**1,3e+03**	**52**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Copper wiring	61	52	100,0
Total	**61**	**52**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	Energy (MJ)	%
Copper wiring	Re-manufacture	90,0	12	100,0
Total			**12**	**100**

EoL potential:

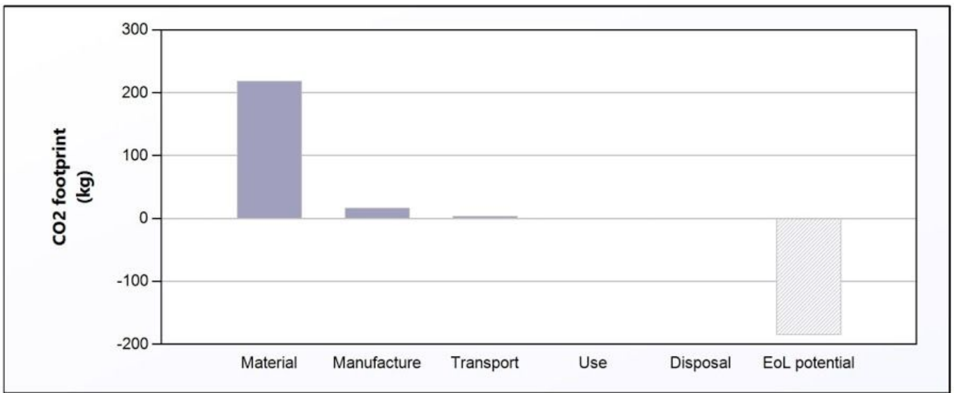
Component	End of life option	% recovered	Energy (MJ)	%
Copper wiring	Re-manufacture	90,0	-3e+03	100,0
Total			**-3e+03**	**100**

Notes:

Summary

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 5 year product life):	48

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Copper wiring	Copper, C10100, soft (electrolytic tough-pitch h.c. copper)	2,0%	61	1	61	2,2e+02	100,0
Total				**1**	**61**	**2,2e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO2 footprint (kg)	%
Copper wiring	Wire drawing	-	61 kg	17	100,0
Total				**17**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Truck from mine to wire manifacturer and from port in Helsingfors to Vaasa	40 tonne (6 axle) truck	8,3e+02	3	79,8
Canal freight from Sthlm to Helsingfors	River/canal freight	4,3e+02	0,76	20,2
Total		**1,3e+03**	**3,8**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Copper wiring	61	3,8	100,0
Total	**61**	**3,8**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	% recovered	CO2 footprint (kg)	%
Copper wiring	Re-manufacture	90,0	0,86	100,0
Total			**0,86**	**100**

EoL potential:

Component	End of life option	% recovered	CO2 footprint (kg)	%
Copper wiring	Re-manufacture	90,0	-1,9e+02	100,0
Total			**-1,9e+02**	**100**

Notes:

Summary

Appendix G

The content of this appendix are included with permission of Ludecke-Freund. This content are presented to work as a support to the morphological box in chapter 4.2.1.2 and 4.2.2.2.

2018 Journal of Industrial Ecology – www.wileyonlinelibrary.com/journal/jie

SUPPORTING INFORMATION FOR:

Lüdeke-Freund, F., S. Gold, and N.M.P. Bocken. 2018. A review and typology of circular economy business model patterns. *Journal of Industrial Ecology*.

Summary

This supporting information shows the 26 CEBMs and CEBM groups that were used for the morphological analysis. This database builds on the initial CEBMs identified in the literature (supporting information S1).

S2-1

Appendix II

Table S2-1 Detailed description of CEBMs as basis for the morphological analysis (n.a. = information not available).

CEBMs		Value proposition		Value delivery		Value capture		Value creation		
		Products	**Services**	**Target customers**	**Value delivery processes**	**Revenues**	**Costs**	**Partners involved**	**Value creation processes**	**Examples**
P1	***"Circular supplies"*** (Accenture, 2014)	recycled inputs; fully renewable, recyclable, or biodegradable inputs	n.a.	manufacturers	replacing virgin materials and "linear" inputs	n.a.	reduction of waste disposal costs; reduction of inefficiencies	n.a.	using waste of third-parties as inputs; using own waste as input; recapturing of waste; reusing of waste	Royal DSM
P2	***"Classic long life model"*** (Bocken et al., 2016)	long-lasting products	repair; maintenance	n.a.	offering long-lasting products and corresponding repair/maintenance services	price premium for longevity and high quality of products	long-term service and product warrantee cost	n.a.	designing long-lasting products	Miele's 20-year life span of appliances; Luxury products with a long lifetime (e.g. luxury watches)
P3	***"Closed-loop production"*** (Clinton and Whisnant, 2014)	n.a.	product take back	n.a.	n.a.	re-engagement of customers to facilitate product take-back	reduction of energy and material costs	n.a.	continuous cycling of material; reduction of waste; recapturing of waste; reusing of waste; biodegradation of waste; composting of waste	Novelis (sources 43% of its aluminum from recycled materials); Interface
P4	***"Co-product generation"*** (Albino and Fraccascia, 2015) / ***"Multiple cash flows / multiple revenues"*** (Pauli, 2010)	co-products based on recycled waste, process residues or by-products	n.a.	n.a.	n.a.	additional revenues from co-products	reduction of energy and material costs; reduction of waste disposal costs; reduced supply risks	n.a.	using waste of third-parties for new products; using own waste for new products; using process residues and by-products as inputs for co-products	British Sugar; McDonalds's "fried for fuel" project; CSC s.r.l. (Italian firm producing concrete)
P5	***"Cradle-to-cradle"*** (Braungart et al., 2007)	cradle-to-cradle certified products; waste-less products	n.a.	n.a.	n.a.	cradle-to-cradle products as flagships to open new revenue streams	n.a.	n.a.	separating, reusing and cycling technical and biological materials	Gabriel (furniture textiles and fabrics manufacturer)
P6	***"Create value from waste"*** (Bocken et al., 2014)	waste as production input	n.a.	n.a.	identify and transfer waste streams	n.a.	reduction of energy and material costs	set up new partnerships (e.g. recycling networks)	using waste of third-parties for new products; using own waste for new products; making use of underutilised capacities and resources	Industrial park Kalundborg
P7	***"Extending product value"*** (Bocken et al., 2016)	used products or components in as-new quality; repaired products; remanufactured products	take back of used products; deposit systems	n.a.	taking back used products from distributors and end-users; offering platforms to sell used products	n.a.	reduction of material costs; increase of labor and logistics costs	collaborations e.g. with retailers, logistics companies, and collection points	recovering products at the end of one product lifecycle; repairing or remanufacturing own products; repairing or remanufacturing products of third parties	Remanufacturing parts in the automotive industry; Gazelle; clothing return at H&M; M&S "Shwopping"
P8	***"Extending resource value"*** (Bocken et al., 2016)	products based on recycled waste	take back of waste materials	green consumers	taking back waste materials	n.a.	n.a.	collaborations e.g. with retailers, logistics companies, and collection points	winning back base materials from waste for new products; using waste of third-parties for new products; using own waste for new products	Interface using fishing nets as a raw material for carpets; RecycleBank issuing reward points for recycling

P9	***"Industrial symbiosis"*** (Beltramello et al., 2013; Bisgaard et al., 2012; Bocken et al., 2016)	waste as production input	cost reductions; supply risk reduction; elimination of third party waste; synergistic partnerships	n.a.	set up geographically proximate collaborations (e.g. eco-industrial parks); matching between waste suppliers and users; sharing of local services (e.g. cleaning, maintenance)	new revenue potential through green image; additional revenues through new IS products	reduction of energy and material costs; reduction of waste disposal costs; reduction of transportation costs	manufacturers	physical exchange of materials, energy, water, and byproducts; using waste of third-parties for new products; using own waste for new products; making use of underutilised capacities and resources	Barton; BB Architects; Kalundborg Eco-Industrial Park; AB sugar and other sugar refiners
P10	***"Online waste exchange platform"*** (Albino and Fraccascia, 2015)	n.a.	bringing together producers and users of waste	waste suppliers; waste users	online-based matching between waste suppliers and users	transaction fees	n.a.	n.a.	identification of gaps between demand and supply of waste	wastetrade.it (Italy); thewastetradecompany.co.za. (South Africa); smileexchange.ie (Ireland)
P11	***"Product life extension"*** (Accenture, 2014)	long-lasting products	upgrading	users of industrial equipment; endusers buying remarketed products	n.a.	additional revenue through extended usage	n.a.	n.a.	designing long-lasting products; repairing, upgrading, remanufacturing or remarketing of products	Appropriate for most capital-intensive B2B segments; B2C companies serving markets where "re-commerce" is common; Google's project "Ara"
P12	***"Product recycling/Recycling 2.0"*** (Planing, 2015) / ***"Recycling and waste management"*** (Kiørboe et al., 2015)	packaging that can be completely emptied	education of consumers to reduce product waste; waste collection; waste sorting; waste recycling	n.a.	n.a.	n.a.	reduction of energy and material costs; reduction of waste disposal costs	suppliers; researchers; key customers; municipality	winning back base materials from used products; winning back base materials from used packaging	Zen Robotics; Norsk Gjenvinning; Icelandic recycling fund; Arla
P13	***"Product transformation"*** (Planing, 2015)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	winning back components from used products	Agito Medical
P14	***"Remanufacturing / next-life sales"*** (Planing, 2015)	used products or components in as-new quality	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	restoring the functionality of products or components	Bosch (remanufactured car parts)

P15	***"Rematerialisation"*** (Clinton and Whisnant, 2014)	n.a.	elimination of third party waste	firms wanting to eliminate their waste to landfill	n.a.	payments from other firms for taking their waste	n.a.	n.a.	winning back base materials from waste for new products	Rubies in the Rubble; Knowaste
P16	***"Repair"*** (Kiørboe et al., 2015) / ***"Reuse / refurbish / maintain / redistribute / next-life sales"*** (Planing, 2015) / ***"Reuse"*** (Kiørboe et al., 2015)	cheaper products; repaired equipment; spare parts	securing uptime and lifespan of products; securing uptime and lifespan of equipment; equipment database; shipping and installation; maintenance; upgrading; renting out equipment	users with constrained budgets	making repaired equipment accessible and affordable	n.a.	n.a.	equipment manufacturers; equipment users	purchasing, refurbishing, remarketing and reselling used equipment; refurbishing and reselling used products	Godsinlösen; Apple Certified Refurbished; Off2Off; Repack
P17	***"Resource recovery"*** (Accenture, 2014)	n.a.	n.a.	n.a.	providing waste as input to third parties; providing waste as input to internal processes	n.a.	elimination of material leakage and corresponding material costs	companies producing large volumes of by-product	recovering products and materials at the end of one product lifecycle; reprocessing of materials; recycling; upcycling	US grocery chain Kroger

P18	***"Service and function-based models"*** (Kiørboe et al., 2015) / ***"Functional sales and management services models"*** (Beltramello et al., 2013) / ***"Deliver functionality, rather than ownership"*** (Bocken et al., 2014) / ***"Functional result"*** (Tukker, 2004) / ***"Pay per service unit"*** (Tukker, 2004) / ***"Access and performance model"*** (Bocken et al., 2016)	n.a.	functionality; result; switching from product to service; user education to shift from owning to using; product maintenance, repair and control	n.a.	providing products to be used; retaining product ownership; taking back used products; specifying functionality or result, but not applied technology	payments per use; payments for functionality; payments for results payments per unit of service (e.g. time, number of uses);	product maintenance costs; product longevity, reusability and sharing reduces costs; reduction of material costs	manufacturers	providing a product; maintaining, repairing and controlling the product; reusing products; using products longer	GH Form; Xerox document management system; Cowell; Scanenergi; launderette
P19	***"Product as a service"*** (Accenture, 2014) / ***"Product lease"*** (Tukker, 2004) / ***"Product renting or sharing"*** (Tukker, 2004)	n.a.	unlimited and individual access to a product (lease); limited and shared access to a product (renting); product maintenance, repair and control	n.a.	providing products to be used; retaining product ownership; taking back used products; specifying functionality or result, but not applied technology	leasing fee; rental fee	product maintenance costs; product longevity, reusability and sharing reduces costs; reduction of material costs	manufacturers	providing a product; maintaining, repairing and controlling the product; reusing products; using products longer	Michelin's "tires as a servce"; clothing hire models; car sharing; Volvo Aero
P20	***"Sharing platforms"*** (Accenture, 2014)	n.a.	collaboration among product users	private persons or organizations with asset overcapacities	users share their overcapacities	transaction fees	n.a.	n.a.	matching owners and users of overcapacities	Lyft
P21	***"Take back management"*** (Bisgaard et al., 2012)	recyclable and decomposable products (and/or packaging)	product take back	distributors and end-users	taking back used products (and/or packaging) from distributors and end-users; retaining product (and/or packaging) ownership	n.a.	reduction of material costs; reduction of manufacturing costs	n.a.	designing recyclable and decomposable products (and/or packaging); taking back used products (and/or packaging)	Desso

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P22	***"Upgrading"*** (Planing, 2015)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	replacing outdated modules or components with superior ones	Modular phone (e.g. Google's "Ara" project)
P23	***"Waste exchange (external)"*** (Albino and Fraccascia, 2015)	waste as production input	n.a.	n.a.	providing waste as input to third parties	additional revenues from selling waste	reduction of energy and material costs; payments to firms taking the waste	n.a.	using waste as an input between different firms	Eco-industrial parks
P24	***"Waste exchange (internal)"*** (Albino and Fraccascia, 2015)	waste as production input	n.a.	n.a.	providing waste as input to internal processes	n.a.	reduced waste disposal costs; reduction of energy and material costs	n.a.	using waste internally as an input	AB sugar and other sugar refiners
P25	***"Waste regeneration systems"*** (Beltramello et al., 2013)	products based on recycled waste	n.a.	n.a.	n.a.	new revenue potential through green image	reduction of material costs	n.a.	n.a.	Brisa; Grundfos
P26	***"Encourage sufficiency"*** (Bocken et al., 2016)	long-lasting products	education of consumers to reduce consumption; warranties; upgrading	customers with high willingness to pay	n.a.	reduction of revenues from product sales; additional revenues from services; price premium for longevity	n.a.	n.a.	designing long-lasting products; repairing, upgrading, remanufacturing or remarketing of products	Vitsoe; Patagonia; Energy Service Companies (ESCOs)

Appendix H

In this appendix examples of meeting protocols from meetings that have been held in the project are presented.

Date: 13 February 2020
Location: ABB CRC, Västerås

Meeting with Motor experts

Interviewees:

Principal Scientist ABB
Principal Scientist ABB

Structure:

Semi-structured meeting with open discussion about the subject.

Agenda:

- Introduction and Background of the project.
- Introduction of interviewees.
- Open discussion about the topic. Questions are asked to the interviewees throughout the discussion.

Questions for the experts:

- The material used in the motors?
- Construction of the motor?
- Life expectancy of the marine motors?
- Most common reason for breakdowns/need for repairs?
- End-of-life handling of the motor? Are ABB responsible for that in some way?
- Are there any BM that supports service?
- Sales and installations of the motor? How does this process work? Integrators?
- Spare parts or similar?
- Efficiency of the motor? IE classifications?
- Special demands on marine motors? What distinguishes marine motors from ordinary motors?
- Old vs new motors? Differences in efficiency etc?

Date: 12 February 2020
Location: ABB CRC, Västerås

Meeting with motor design expert

Interviewees:

Principal scientist ABB

Structure:

Semi-structured meeting with open discussion about the subject.

Agenda:

- Introduction and Background of the project.
    - Motors life cycle
    - Marine motor, LV, on-deck etc.
    - BM→ Circular economy. Extend use.
- Introduction of interviewee.
- Open discussion about the topic. Questions are asked to the interviewees throughout the discussion.

Questions for the experts:

- Design of motors used in marine environments? Protection against the corrosive, humid and cold climate?
- What parts of the motor design are the most important when the products reaches end-of-life?
- Does the “protective” design to make the motor harder to repair/remanufacture etc?
- Are there any focus on making the design sustainable? Or only to improve efficiency?
- Important design parts of extending the life time of motor?
- Thoughts on:
    - Remanufacturing
    - Repairs
    - Designing motors to extend life time

Date: 23April, 2020
Location: ABB CRC, Västerås

Meeting with ABB Service

Attendances:

Students from Linköping University
Principal scientist ABB CRC
Principal scientist ABB CRC
Digital lead and Business development, ABB Motion
ABB Service Sundsvall
Product manager, ABB Västerås

Agenda:

- Introduction of all participants of the meeting (~ 5 min)
- Presentation of our project (~ 5min)
- Short presentation by the Linköping students (~ 5 min)
- Presentation by ABB Service- What are done today and what future work are to be done with Circular economy
- Q&A and open discussion about CE, service etc.

Questions for the experts:

- What can be done to extend life of motors?
- How does the service/maintenance organization work today?
- Risks of using recycled material?
- Biggest challenges of repairing motors?
- Most common reasons of failure/breakdowns?
- Are the motors worth repairing? Why-Why not?
- Thoughts about a remanufacturing line? Possible to accomplish?
- Are there a possibility to repair/remanufacture motors today?
- Are the customers desiring repaired/sustainable/remanufactured motors today?
- Does the motors lose efficiency over time?