Life cycle assessment of a combustion engine - mapping the environmental impacts and exploring circular economy

Master's thesis in Supply Chain Management

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Cover: VEP4 engine from Aurobay. The picture is used with permission from Aurobay.

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Abstract

The need for sustainable transportation has rapidly increased the interest for sustainability in the automotive industry. It is an industry that is moving towards electrification as the primary solution to reduce the environmental impact. Previous LCA-studies have often solely looked at CO_2-emissions making BEVs an attractive solution, often without considering other environmental impacts.

This master thesis study aims to broaden the spectrum of environmental impacts in the automotive industry by conducting an LCA from cradle to grave including multiple impact categories. The product studied is a state of the art internal combustion engine (ICE) produced by Aurobay, Powertrain Engineering AB. This LCA helps both understanding the environmental impact over the life cycle of an ICE as well as exposing potential improvements in the life cycle to increase its sustainability.

The study results show how dominant the user phase emissions are for climate impact emphasising the need for alternatives to the traditional fuels. It also shows the significance that the production of parts have with aluminium and steels having a large role. Furthermore the inclusion of multiple impact categories highlights the impact from lithium ion batteries and copper, impacts that are overlooked when CO_2 is the only measure of the environmental impact.

The results from sensitivity analysis showed the significance of the location of material sourcing on the environmental impacts and how beneficial and influential the use of recycled materials in the engine is with respect to the environmental impact. More research is needed but the study mapped the environmental impacts for a broader spectra of impact categories than usually studied in the automotive industry. Further studies could help exposing the biggest environmental burdens that actually lies in order to move towards a sustainable transportation.

Keywords: LCA, ICE, Aurobay, Sustainability, Cradle to grave, Sensitivity analysis, Automotive industry, Sustainable transportation.

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Abbreviations

ICE: Internal combustion engine

VEP: Volvo engine petrol

MP: Medium power

WLTP: World harmonized light-duty vehicle test procedure

GHG: Greenhouse gas

LCA: Life cycle assessment

LCI: Life cycle inventory

LCIA: Life cycle impact assessment

GWP: Global warming potential

CML: Centrum voor Milieukunde Leiden

AP: Acidification potential

ADP: Abiotic depletion factor

EP: Eutrophication potential

HTP: Human toxicity potential

POCP: Photochemical ozone creation potential

EOL: End of life

BOM: Bill of material

KERS-battery: Kinetic energy recovery system - battery, a li-ion battery storing energy recovered from braking that can be used to boost the engine

HPDC: High pressure die-casting

BIGS: Belt integrated starter-generator

APAC: Asia-Pacific

EAS: Engine as shipped

1

Introduction

This chapter explains the background on importance of conducting life cycle assessment, responsibility of automotive industries on emissions, Aurobay's background and lastly the main aim of this thesis study along with the research questions.

1.1 Background

Environmental change and global warming led to the signing of the Paris agreement in 2015 where countries agreed to take action in order to prevent the global average temperature from increasing more than 2 ℃ [1]. The Paris agreement puts pressure on countries to reduce their emissions and the EU has committed to become climate neutral by 2050 [2]. Since then, governments have increased legislation to achieve emissions reduction at the same time as favouring economic growth. By increasing costs on emissions and harmful activities while discounting activities that favours sustainability, organisations need to change the way they operate in order to stay competitive and profitable.

Thus, it is now in the automotive industries best interest to increase sustainability in their business and reduce emissions. Mapping the environmental footprint for products and activities in the organisation is a starting point for a sustainability transformation. Life cycle assessment is a holistic way of mapping the environmental footprint over a life cycle. This way emissions over the life cycle of a product or a process for example, can be visualised and hotspots in the life cycle with high emissions become exposed. This can facilitate the process of deciding where resources should be focused to reduce environmental footprint.

It's been identified that an internal combustion engine with fossil fuels contributes to CO_2 emissions of 10 to 20% during production and 80 to 90% during operation [3]. It was also found that end of life including recycling was responsible for 1% emissions [4]. The percentage share in regards to production was identified to be caused mainly by materials in the supply chain [4]. Hence in order to address these emissions, life cycle assessments can be used by the automotive industries for managing and improving their environmental performances. Life cycle assessments are mainly based on ISO 14040 and 14044 standards which is the most frequently used methodology by the automotive industries [4]. Life cycle assessment can also be seen as a voluntary tool as it would support strategic decisions made internally within companies in regards to product development [4].

1.2 Company background

Aurobay is a manufacturer of internal combustion engines for cars with Volvo cars and Geely Holding as customers as well as owners. The car industry is going through a transformation with more focus on electrification and the combustion engine is being questioned. Volvo cars has set the goal to be climate neutral by 2040 and Geely Holding by 2045 [5] [6]. In a time where people are questioning the combustion engines, Aurobay is facing a big challenge and needs to act in order to stay competitive.

Hence, Aurobay has ordered this project to make a life cycle assessment on one of their engines, the VEP MP Gen3, to see what environmental impact the engine has from cradle to grave. They are also interested to know the major contributors in the life cycle stages of the product, what changes can be done in the product life cycle to lower the environmental impact and what effect those changes may have. As the engines to a large extent consist of metals and polymers, metals that have a high environmental impact, the aspect of resource efficiency and circular economy is also highly relevant.

Aurobay as a company aims to improve their sustainability approach by focusing on three main core areas such as climate change, circular economy, ethical and responsible business [7]. With respect to climate change, Aurobay aims to reduce emissions responsible from their engines, factories, upstream as well as downstream activities. Aurobay's factory located in Sweden already makes use of 100% renewable energy and is focusing on increasing this percentage share in other facilities within the supply chain and operations [7].

With respect to the circular economy, Aurobay has designed its products and manufacturing processes in a way to minimise most of the waste being generated. Aurobay pushes their suppliers in order to promote achieving a circular economy. Aurobay does this by setting higher standards for recycled content of materials like plastics, steel and aluminium during the procurement process [7]. With respect to ethical and responsible business, Aurobay ensures to work with compliance and ethical business practices to support sustainability. Aurobay also makes sure that the ethical practices are followed throughout their supply chain [7].

1.3 Aim

The main aim of this thesis study is to create a baseline cradle to grave life cycle assessment for one of the engines produced by Aurobay. The reason behind conducting this life cycle assessment study is to map the environmental footprint of products and activities carried out by Aurobay in order for a more sustainable transition to occur. Apart from conducting a baseline life cycle assessment, a sensitivity analysis is aimed to be performed in order to identify the improvements potential with the baseline. This is done by utilising what-if scenarios.

1.3.1 Research questions

The research questions that are addressed by doing the life cycle assessment study are the following:

- From cradle to grave: What is the baseline environmental impact of a state of the art internal combustion engine as installed, VEP MP Gen3? What are the major contributors in the steps of life cycle assessment of the considered engine?
- How can the baseline environmental impact be influenced by applying strategies that focus on resource efficiency to the life cycle of a VEP MP Gen3?

2

Literature review

This chapter includes definition of life cycle assessment, it's key features and limitations, a literature review on life cycle assessment framework to get an idea about the subject revolving the thesis and other LCA-studies.

2.1 Definition of LCA

According ISO standard 14040, life cycle assessment studies the environmental aspects and the potential impacts throughout the life cycle of a product i.e. cradle-to-grave analysis from raw materials acquisition through production, use and disposal [8]. Life cycle assessment is a tool used to learn more in detail about a product system. It is used to analyse the environmental impacts caused by the product system to focus mainly on the most important environmental behaviour indicators responsible for the negative impact thereby finding ways to minimise the effects caused by them [9].

2.2 Key features of LCA

Life cycle assessment (LCA) is quantitative in nature and enables comparison of environmental impacts of different product systems and processes. LCA plays a vital role in enabling the reduction of environmental impacts by identifying the environmental impacts in the stages of the product system that has caused more damage thereby increasing eco-efficiency [10]. Eco-efficiency is a management strategy that uses fewer resources while producing more goods and services thereby creating lower pollution and waste [11]. LCA aims to protect the environment that is required to attain environmental sustainability. LCA can assess several environmental impacts such as climate change, ozone depletion, acidification, eutrophication, photochemical ozone formation, eco-toxicity, human toxicity, particulate matter formation, land use, water use and abiotic resource use. LCA can be used to cover multiple environmental impacts to avoid burden shifting that happens when efforts taken on lowering one type of environmental impact leads to an increase in another type of environmental impact [10].

2.3 Limitations of LCA

The generalisations and specifications required for modelling the product system and its respective impacts prevent LCA from calculating the actual environmental impacts. LCA calculates potential environmental impacts with consideration towards uncertainties in mapping of emissions and resource use. The modelling of impacts and calculated impacts are being aggregated over time and space. The model is based on average performance of the processes and does not focus on problematic issues like accidents at industrial sites [10].

2.4 Life cycle assessment framework

According to ISO standard 14040:1997, the LCA framework consists of 4 phases: goal and scope definition, inventory analysis, impact assessment and interpretation. Each of these phases are interdependent [12]. In further sections, the activities performed in each of the four phases will be briefly explained and summarised below in the figure 2.1

2.4.1 Goal definition

The goal definition is the first phase of LCA. The goal should elaborately define and describe the main purpose of the study. According to the ISO standard requirements, the goal definition contains 6 aspects; intended application of the results, reasons to carry out the study and decision context, target audience, commissioner of the study and influential actors, comparative studies to be disclosed to the public and limitations due to methodological choices [10].

2.4.2 Scope definition

The scope definition is also part of the first phase of LCA. The scope should define and describe the product system and how it has been assessed. It should ensure that the goal is met along with the assumptions and limitations considered under study. The scope definition contains 9 scope items; key concepts, object of assessment, life cycle inventory (LCI) modelling framework, handling of multi-functional processes, system boundaries and completeness requirements, representativeness of LCI data, preparing basis for impact assessment, need for critical review and planning the reporting of results [10].

2.4.3 Inventory analysis

The inventory analysis is the second phase of LCA. It is the most time consuming part of the study. The inventory analysis includes collection and compilation of data from different sources needed for inputs and output flows of every unit process that serves as a basis for the subsequent life cycle impact assessment phase [10].

2.4.4 Life cycle impact assessment

The impact assessment is the third phase of LCA. In this phase, life cycle inventory information on elementary flows is translated into environmental impact scores that are done with software [10]. The life cycle impact assessment involves 5 steps, first three are mandatory elements and last two are optional elements [10]. The mandatory elements are selection of impact categories, classification and characterisation. The optional elements are normalisation and weighting [10].

2.4.5 Interpretation

The interpretation is the fourth and last phase of LCA. In this phase both results from inventory and impact assessment will be combined to provide an unbiased and complete account of the LCA study [13]. Interpretation consists of 3 main elements, identifying the significant issues from life cycle inventory results and life cycle impact assessment phases of the study, then evaluating the results using sensitivity analysis, completeness and consistency checks, lastly conclusions are made keeping in mind the limitations and finally some recommendations are provided [13]. Here the sensitivity analysis of a model refers to the variation in the results of the model based on the changes made to the input parameters of the model [10].

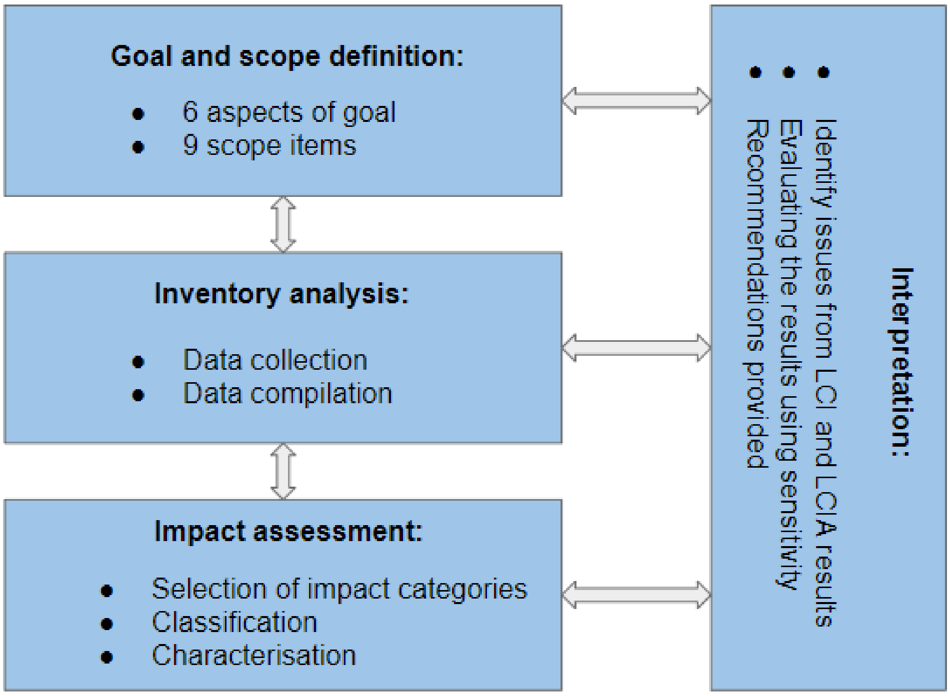


Figure 2.1: *Summarised 4 phases of life cycle assessment framework [11]*

2.5 Iterative nature of LCA

The uncertainties in the LCA would be reduced by means of repeated iterations. Therefore, LCA is of iterative nature as iterations are carried out until the uncertainty of the LCA results are reduced and sufficiently small in order to meet the goal and scope of the study [10].

2.6 Other LCA-studies

Life cycle assessment has traditionally not been a common part of the operations of a manufacturer in the automotive industry, but there are indications on an increase in the interest for LCA's [14]. Taking responsibility over the entire value chain and life cycle is relatively a new way to approach sustainability in the manufacturing industry [15].

Ibrahem & Sjöqvist [14] conducted a literature study on LCAs in the automotive industry and concluded that global warming potential was the dominant impact category that companies assessed. It measures CO_2 equivalents and only considers emissions that has an effect on the global warming. A reason for this being the greenhouse gas protocol (GHG) which is a well established global accounting standard. Furthermore Ibrahem & Sjöqvist discusses that the GHG protocol shouldn't be used to assess the overall environmental footprint as there are environmental impacts which the GHG protocol does not include.

Volvo Cars made an LCA on their Volco C40 and XC40 comparing the carbon footprint of a car with an ICE to a BEV. The study was made on a cradle to grave analysis and studied a product with a similar life cycle as the engine in this study. Assumptions in their study stated that inventories do not include inputs from infrastructure and manufacturing buildings, nor business travels and R&D. Exceptions from these assumptions might exist if processes chosen in the databases already contained such inputs. The report also discusses the impact that the methodology has on the result and concludes that it is not appropriate to compare studies with each other if the methodology isn't the same [16].

Aggregations in the bill of material of a product is a way to reduce the workload and make data manageable. Applying a 1% weight cut off and only look at parts above that weight significantly affects the workload, yet manage to maintain a level of precision seen to be reasonable [17]. However, doing similar aggregation for number of substances considered in the parts have a the same type of workload reduction but effects in loss of precision has a bigger impact than for weight cut-off [17].

The review of other LCA-studies stated that a life cycle assessment focusing only on one impact category isn't enough to assess the environmental impact of a product. Studies connected to the automotive industry also gave insights in the complexity that life cycle assessments in this industry brings. Cars and engines consists of a vast number of details and the different life cycle phases make use of buildings and infrastructure that can be challenging to include. Hence assumptions and aggregations are useful in order to reduce workload and make the study manageable. However, it is important to assess the effect these assumptions and aggregations have on the result and take this in to consideration when assessing the environmental impact result.

3

Method

This chapter describes the goal and scope of the study and sets the framework for how the LCA was carried out.

3.1 Goal

The main goal of the study is to first create a baseline LCA for Aurobay's latest generation mild hybrid petrol engine, VEP MP Gen3. The second goal is to analyse how baseline environmental impacts will be influenced by applying potential what-if scenarios. The commissioner of this LCA study is Aurobay and the influential actor of this LCA study is the supervisor and examiner assigned by Chalmers for this thesis. The LCA conducted for this study is an attributional stand-alone LCA.

Aurobay aims to use the LCA results to document environmental performance of their engine to identify environmental hotspots that have been most impacted in the product system thereby to evaluate improvements potential with changes done to their product system. Aurobay does not intend to use the results to compare their products with other competing products that perform similar functions in terms of environmental performance. Aurobay mainly focuses on understanding their product, how it affects the environment and what impact it has on the environment. Aurobay intends to present and communicate the LCA results within the organisation for internal purposes like product development over external purposes like conveying benefits of products to their customers.

3.2 Scope

The product to be analysed for the LCA study is Aurobay's latest generation mild hybrid petrol engine, VEP MP Gen3. The engine will be analysed in two cases, one as a baseline and other as a sensitivity analysis for assessing strategies with what-ifs scenarios to establish potential benefits incurred with changes in manufacturing location and use of recycled material in engine production.

3.2.1 System definition

Aurobay's product system consists of unit processes including refining and material production, assembling phase at Skövde and Torslanda, distribution phase, use phase and end of life phase. The product system can be divided into foreground and background systems. The foreground system consists only of the inbound transports and assembling phase at Skövde which is controlled and managed by Aurobay. The background system consists of unit processes like refining and material production, outbound transports, assembling phase at Torslanda, use phase and end of life phase which is not much controlled but influenced by Aurobay. The product system along with all the unit processes, flows, foreground and background systems are represented in the flowchart in figure 3.1.

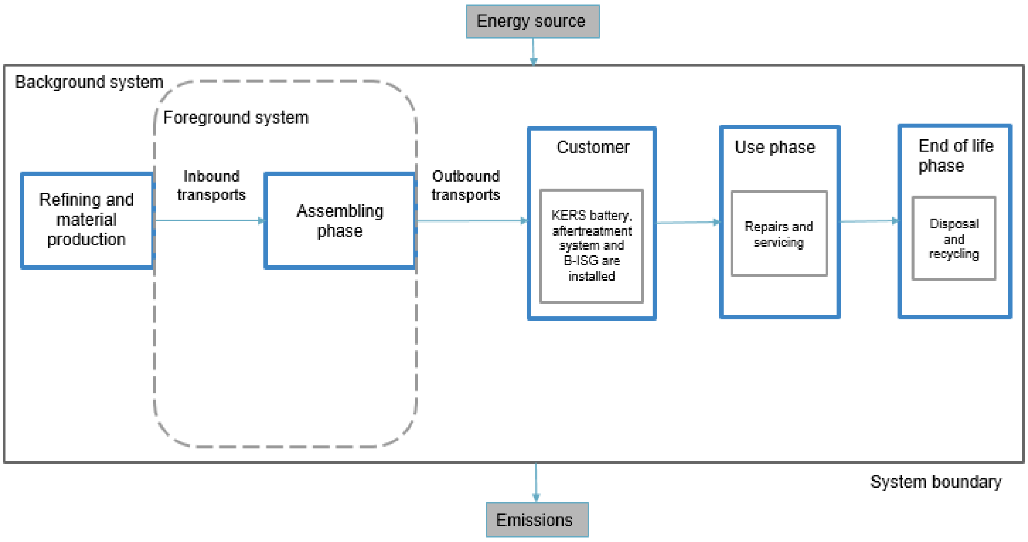


Figure 3.1: *Product system of Aurobay's engine*

The raw materials are extracted from the earth's crust and are then refined to produce materials. The materials are then processed and refined at the suppliers. The components produced are transported from the suppliers across the globe to the production site situated at Skövde, either directly or through consolidation centres. At the production site, the components are assembled to produce the engine. The engine is then shipped from the production site to the customers location i.e. Volvo Cars Torslanda plant. At the customers location, final installations take place where the engine, KERS battery, aftertreatment system and BIGS (Belt integrated starter-generator) gets installed in the car. After the final installations, the car is shipped as a final product to the end user's location.

For the use phase, the car was assumed to be used until it has been driven for a distance of 350,000 km or if it was used over a time period of 15 years. Thus, user phase lasts for 350 000 km or 15 years since they are seen as equivalent in this case. The respective repairs and servicing data of the engine during the use phase are included in the modelling. For modelling repairs, the data on repairs for the first 12 months in service was assumed to be extrapolated for the entire life time of engine. For modelling services, servicing and exchanges were assumed to be done in accordance with the servicing intervals provided by Aurobay. Here an assumption was made that the replaced parts during servicing was sent to the recycling station which is included in the modelling of use phase.

After 350 000 km or 15 years, the end of life phase comes next. The car is assumed to be driven to the recycling station where the engine is scrapped. Then it would be recycled or disposed of by means of incineration or landfill depending on the material type of the engine and how waste was managed in specific countries chosen under study. The end of life involves both disposal and recycling stages.

3.2.2 Object of assessment

The object of assessment includes function, functional unit and reference flow of the studied product. For Aurobay, the function of the studied product i.e. the engine is to provide the main source of power to the car [18]. The functional unit of engine is considered as the transport service provided for a certain car running over a certain driving cycle for a distance of 350 000 km. The car chosen for the study is a Volvo XC60 AWD of model year 2020, the driving cycle chosen is Worldwide Harmonised Light Vehicles Test Procedure (WLTP). The reference flow then becomes one VEP MP Gen3 engine for this study.

3.2.3 LCI modelling framework

The LCI modelling framework is assumed to be attributional for both baseline scenario and sensitivity analysis. The attributional or descriptive modelling is meant to be used when focus of the study is to describe the environment related physical flows of the life cycle of the product system [19]. The baseline scenario was assumed to be attributional as it was based on the current state of the product system. While the sensitivity analysis was also assumed to be attributional as it was just based on changes made to the current state of the product system [20].

3.2.4 Handling of multifunctionality

For this study, the primary function of the engine is only considered and secondary function of the engine is not included. Hence, there is no handling of multifunctionality involved in the study. Also, being a stand-alone LCA involves no comparison of products, hence there is no sub-division, system expansion or allocation in regards to functionality of the product in this study.

For the use phase, fuel consumption and emissions of the car were assumed to be allocated based on the share of total weight of engine in relation to the car i.e. 8% respectively. While the car as a whole has one function, the different parts have different functions. For this as a reason we have used weight allocation where only a part of the total impacts to the engine is considered.

3.2.5 System boundaries

The LCA study is modelled from cradle to grave i.e. the product system of Aurobay consisting of unit processes starting from refining and material production, including assembling phase, distribution phase, use phase and finishing with end of life phase.

For the baseline scenario, datasets used for refining and material production were specific to Europe only since the majority of suppliers were located in Europe. For the cases where Europe wasn't applicable, a global approach was chosen. For one of the sensitivity analyses, a more global approach was chosen for refining and material production. In this study, only the emissions covered by the chosen impact assessment method are considered. The emissions related to infrastructure are excluded for this study unless the database holds underlying data on it in the processes chosen to model the LCA.

Apart from the above mentioned system boundaries, there are time, geography and technology related system boundaries [13]. In regards to time, the boundary is set until the lifetime of the engine under study which would be 15 years in that case. The production and assembling of the engine at the production plant was set to Skövde, Sweden. The engine being shipped was set to Gothenburg, Sweden. The use phase and the end of life phase are limited to be assessed in Sweden and Poland. A sensitivity analysis performed to analyse the baseline after application of potential what-ifs is limited to focus only on the Swedish use case meaning that Poland will be excluded in this case for both use phase and end of life phase. In regards to technology, this study involves the current technology in use.

3.2.6 Aspects of LCA modelling

The software used for modelling the LCA of the product under study is openLCA. OpenLCA is a free open source software that offers a calculation engine for doing LCA. This software was mainly developed to make life cycle assessment and sustainability assessment more affordable and accessible [21]. The database utilised for this study is Ecoinvent of version 3.8. Ecoinvent is the most popular LCA database available on the market. This database consists of international industrial LCI data [22]. The datasets available in the ecoinvent covers a wide range of processes, products and services. For example, from extraction of resources to management of waste and from the building materials to the food. It also contains a wide range of emissions that could be translated into environmental impacts with all the LCIA methods available [23].

Processes and sub-processes containing the material and energy flows corresponding to the phases of the life cycle were mapped and connected to each other, creating the cradle to grave life cycle of the product. Technical data on the product as well as datasets for the processes operated by Aurobay was provided by the company. A visit to the production site of the product was conducted to study the manufacturing process of the engine. Ecoinvent as well as supporting literature reviews was used for secondary data.

When modelling the life cycle in OpenLCA, a set of activities are combined to build a process corresponding to a part of the life cycle. The activities in the chosen database are structured on a geographical level i.e. each activity corresponds to a geographical region depending on where the activity takes place. Activities are chosen to replicate characteristics of activities that take place in the actual life cycle. For sourcing of materials, it was assumed that material is sourced as close to the suppliers as possible. When activities couldn't be chosen to meet this criteria, a global approach was applied.

3.2.7 Impact assessment methods

The impact assessment method used for this LCA study is CML (Centrum voor Milieukunde Leiden) version 4.8 from 2016. The method was created by the University of Leiden in the Netherlands in 2001. CML contains over 1700 different flows [24]. It holds both midpoint and endpoint categories, however only midpoint categories are assessed and endpoint categories are excluded in this study in order for the results to be transparent. Midpoint categories to be assessed are acidification, climate change, depletion of abiotic resources (energy and material resources), eutrophication, human toxicity and photochemical oxidation.

Acidification occurs as a result of protons being released into the ecosystem from certain substances. These emissions thereby increase acidity i.e. decrease in pH of soil and water, thus leading to the environmental issue being acid rain. Acid rain or acid deposition is mainly caused when gases such as sulphur dioxides, nitrogen oxides and ammonia react with water in the atmosphere. Acidification potential (AP) can be divided into terrestrial and aquatic ecosystems. In regards to the terrestrial ecosystem, growth of forests will be devastated. In regards to aquatic ecosystems, formation of acid lakes and wildlife will be affected in lakes. AP is measured by Kg Sulphur dioxide (SO_2) equivalents [24].

Climate change occurs as a result of change in the global temperature caused by the release of greenhouse gases like carbon dioxide, chlorofluorocarbon, methane, nitrous oxide etc. mainly due to human intervention. Climate change might give rise to climate disturbances like powerful cyclones, increase in sea levels, temperature disturbances like decrease in biodiversity, spread of disease and desertification. Global warming potential (GWP) is measured by kg carbon dioxide (CO_2) equivalents [24].

Depletion of abiotic resources occurs mainly due to the unsustainable use of both renewable and non-renewable resources that leads to decrease in availability of the resources. Therefore this might further lead to scarcity of the resources. Depletion of abiotic resources can be divided into depletion of energy resources and depletion of material resources. Where the energy resources refers to fossil fuels, hydropower etc. and the material resources refers to minerals, metals etc. Abiotic depletion factor (ADP) for energy resources is measured by MJ (MegaJoule) which for this category means MJ of fossil fuels. ADP for mineral resources is measured by Kg antimony (Sb) equivalents, where antimony is a chemical element [24].

Eutrophication occurs as a result of emissions such as ammonia, phosphorous, nitrogen oxides being released to water and air thereby causing abnormal productivity. For example, eutrophication results in excessive growth of plants such as algae that severely affects the animal population and water quality. Eutrophication potential (EP) is measured by Kg phosphate (PO_4) equivalents [24].

Human toxicity occurs as a result of harmful and hazardous chemicals being released into the environment thereby affecting human health by means of respiratory diseases, cancer and non-carcinogenic effects. Human toxicity potential (HTP) is measured by Kg 1,4-dichlorobenzene (DCB) equivalents [24].

Photochemical oxidation known as ground level ozone occurs as a result of reaction of nitrogen compounds with volatile organic compounds in the presence of sunlight and heat causing emission of substances such as sulphur monoxide, nitrogen oxide, ammonium etc. to the air. This ozone present in the ground level at higher concentrations are toxic to ecosystem quality and human health. Photochemical ozone creation potential (POCP) known as summer smog is measured by Kg ethylene(C_2H_4) equivalents [24].

3.2.8 Critical review and reporting of results

There is no critical review involved for this study. The results of the thesis study are planned to be presented for Chalmers University of Technology and then to be presented internally within Aurobay (Powertrain Engineering AB). The report will be published and accessible to everyone through Chalmers platform.

3.2.9 Assumptions and limitations

The LCA is limited to study only the Swedish plant located at Skövde. The chinese plant located at Zhangjiakou is excluded for this study. To limit the scope of work for this study, only the first tier suppliers are considered. An assumption was made that suppliers source raw materials close to their own production sites i.e. suppliers located in Germany would source and produce materials in the same location as well. For the baseline, LCA was modelled only with primary materials and no recycled materials were considered. For the sensitivity analysis, LCA was modelled along with the recycled materials. The further assumptions made will be explained in the section 4.

4

Inventory analysis

This chapter describes inventory analysis in detail involving collection and compilation of data for modelling the product system of Aurobay's engine. The unit processes described below are refining and material production, distribution phase including logistics involved in the product system, assembling phase, use phase, end of life phase and lastly the sensitivity analysis of baseline after application of potential what-ifs.

4.1 Materials production and refining

The input from production of parts and components was based on the bill of material (BOM) for the engine to be studied. In this study, standard parts such as screws, nuts and plugs etc. are excluded from the BOM and won't be studied due to time limitations. The standard parts make up for about 4% of the weight of the product. However the BOM still contains more than 200 part numbers and over 5 000 items making up these 200 part numbers. Since the components are being assessed manually and materials as well as production processes are to be assigned to each of the components, aggregations and assumptions were applied to manage the BOM. A cut off criteria was set to 1 gram meaning that the study will only include items that weigh more than 1 gram. This reduces the number of items down to 780, while still having more than 99% of the total weight in the reduced BOM.

A second aggregation filter was applied when looking at the material categories. The engine contains hundreds of different materials with different production processes and surface treatments. As a way to make the modelling and processing of the BOM manageable, the specific materials were aggregated into material categories and each material category was assigned a specific series of processing methods based on what processes are the most common for that material category [25]. Therefore each material category was assigned a set of refining processes that together with the material production constitute the production of a component. Then the production process of the components were modelled in OpenLCA by creating a production process for each of the selected material category and then weights were applied from the BOM to each material category. The material categories are shown in appendix A.1. It was known that Aurobay uses recycled material in their engines, however the share of recycled material for the respective material categories was unknown and also varies over time based on the supply of scrap. Hence no recycled material is considered in the model, only the use of primary or virgin material was modelled for the baseline.

In regards to the processing methods, a few assumptions were made based on the material category. The non-ferrous metals including aluminium, copper, nickel alloy and Zinc were assumed to be die-casted [26]. The ferrous metals including cast iron, iron, magnet and steel were assumed to be lost wax casted [27]. The polymers including plastics like thermoplastics and thermosets and rubbers including elastomers were assumed to be injection moulded [28]. These assumptions are summarised below in the table 4.1. The remaining assumptions made with respect to the processing methods for lubricants, ceramics and glass will be presented in appendix A.1.

Table 4.1: *Processing methods for material categories*

	Processing applied
Non-ferrous metals	Die-casted
Ferrous metals	Lost wax-casted
Polymers	Injection moulded

Thus material categories and processing methods are listed in appendix A.1 together with the chosen datasets in OpenLCA. However, OpenLCA does not have production processes for all materials and in the case of having a material category that lacks an exact replica in OpenLCA, an approximating material available in OpenLCA was used which is also displayed in appendix A.1. Hence there are 55 unique material categories implemented in the model that represent the entire BOM. Each component is divided into one of the material categories and the accumulated weight of the components in each category is calculated and implemented in the LCA model.The materials distribution in the engine is shown in figure 4.1.

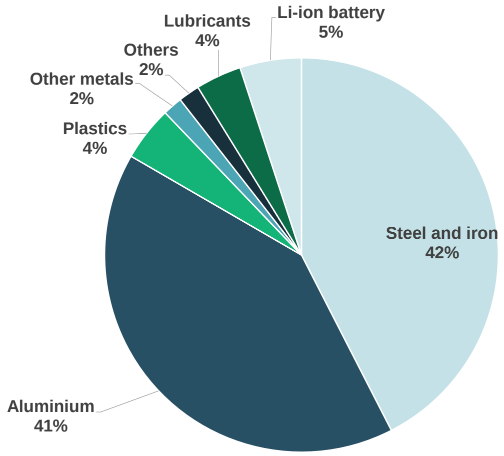


Figure 4.1: *Materials distribution in engine and aftertreatment system by weight*

4.2 Distribution phase

A majority of the parts and components in the engine are produced and finalised at suppliers and are then shipped as components to the production site at Skövde. Aurobay has over 300 suppliers delivering components by road, rail, sea and air. Most of the suppliers are located in Europe but significant volumes are also transported from Asia. The goods are sent from suppliers directly to the production sites or through cross docking centres located in Gothenburg, Maintal, Jirny, Herne and Destdonk. A cross-docking station is a site that unloads, consolidates and directly reloads the inbound inventory goods onto the outbound truck for speeding up the shipping cycle [29]. An aggregation of supplier locations was made that a location in each country that holds suppliers represents the supplier location for all the suppliers in that country. Routes between supplier locations and destinations, both cross docking and production sites, were drawn and the travelled distance for each route was calculated. Aggregated supplier locations are listed in appendix A.2 and can also be seen in figure 4.2 and 4.3.

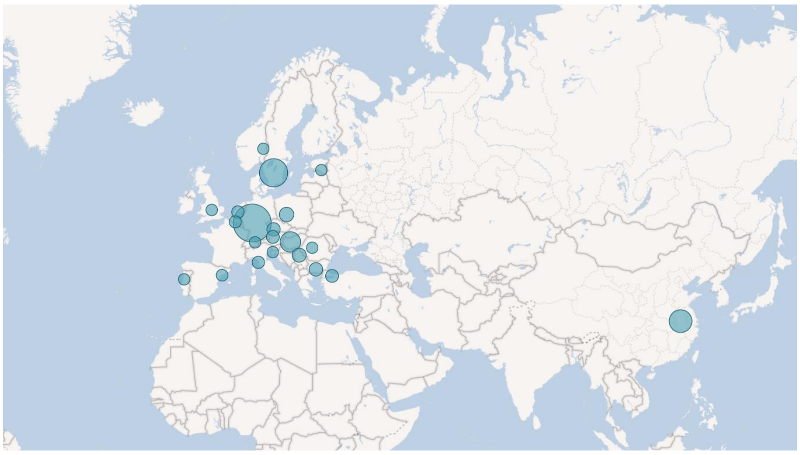


Figure 4.2: *Map showing the countries where Aurobay's first tier suppliers have their HQ, the bubbles shows the volumes shipped from each country*

Figure 4.3: *Map showing the locations of the cross-docking centers used by Aurobay, the bubbles shows the volumes passing through each cross-docking center*

To the shipping routes, shipping data containing the mode of transport and weight of the transported goods for three months of production was added. The processed shipping data was divided by the number of engines produced during the corresponding time to attain the shipping from first tier suppliers associated with the engine, see equation 4.1. Suitable transportation activities in OpenLCA were applied, details can be seen in appendix A.3.

$$\sum \frac{Shipping \quad volume(tonnes) * distance(km)}{Production \quad volume(pcs)} = \frac{ton * km}{engine} \tag{4.1}$$

The components are then assembled to produce the engine. After being assembled, the engine is shipped by truck from the production site to the Volvo Torslanda plant. At the Volvo Torslanda plant, final installation takes place and the engine as installed in the car is assumed to be shipped to the end user's location.

The end users were assumed to be from Sweden and Poland. A further assumption was made that the end users from Sweden collected the cars directly from the Torslanda plant. Whereas the end users from Poland were assumed to collect the cars from the dealers in Poland. In this case, the car was assumed to be shipped by truck from Torslanda plant to Karlskrona ferry port and from there the shipment would reach Gdynia ferry port. From there the shipments were assumed to be reaching by truck to the dealers location from the Gdynia port. In the user phase, the warranty items were assumed to be shipped within Gothenburg, Sweden meaning that items are shipped from Gothenburg to the servicing station for the Swedish scenario. For the Polish scenario, the warranty items were assumed to be shipped from Gothenburg to Gdynia, Poland where servicing takes place. For the end of life scenario, an assumption was made that the end user drives the car themselves to the nearby recycling station.

4.3 Assembling phase

The assembly phase takes place both at Aurobay's plant where the EAS is assembled, but also at the customer in Torslanda where the engine is installed in the car and the aftertreatment system as well as the KERS-battery is added. Following section will elaborate on the inventories included in the assembly phases.

4.3.1 Assembling at Skövde

The components arrive from the first tier supplier's location across the globe to the production site at Skövde where the assembling of the engine takes place. Inputs of the assembling phase are components from suppliers, processing materials such as cutting fluids, electricity and hot water. Outputs are waste and an engine to be shipped. Data sets for inputs and outputs cover the entire production plant over a certain period of time. They are therefore divided by the production volumes to get the flows for one engine.

4.3.2 Assembling at Volvo Cars Torslanda

From the production site, the engine is shipped to the Volvo Torslanda plant who are the customers of Aurobay. The final installation then takes place which means that the inputs are an engine, KERS-battery which is a lithium ion battery, aftertreatment system and BISG that needs to be installed in a car. Then the output would be an engine as installed in the car which will be shipped from Volvo Torslanda plant to end users.

4.4 Use phase

The user phase is modelled for two different user cases to investigate how the location of the user phase affects the environmental impact. In this thesis the locations chosen were Gothenburg in Sweden and Gdynia in Poland. The user phase includes driving the car for 350 000 km with fuel consumption [30] and tailpipe emissions according to the WLTP test cycle. Fuel consumption and tailpipe emissions are allocated on a weight criteria, allocating the tailpipe emissions from the car depending on the weight of the subsystems in the car. The share of tailpipe emissions for the studied product system are 7.9% as the product system holds 7.9% of the total weight of the car. User phase data set is shown in appendix A.5.

4.4.1 Repairs and servicing

Aurobay provides service intervals for the engine where subsystems are serviced and exchanged during the life cycle to maintain the function of the engine and reduce the risk for failure. The service intervals are listed in appendix A.6 and parts included in the service intervals are exchanged accordingly. Hence there is an input in the user phase of parts to be serviced, recycling of replaced parts also takes part in the user phase. Details on recycling are described in section 4.5.

In order to model repairs needed when failure occurs, data on repairs for the first 12 months in service is extrapolated for the entire life cycle assuming a constant rate of repairs.

4.5 End of life

The end of life phase was modelled for two different cases to investigate how the location of the end of life phase affects the environmental impact. The two countries assessed were Sweden and Poland. After the end of life of the engine, the car is assumed to be driven to the recycling station where the engine will be scrapped. Then the disposal ways were assumed based on the material type of the engine and based on waste management carried out in specific countries chosen under study.

For Sweden, metals, plastics, fluids, ceramics and glass were assumed to be recycled. Only rubbers were assumed to be incinerated. The assumptions related to end of life for Sweden were made with the help of information provided by Stena recycling

AB [31] and EU waste legislation [32]. The assumptions made for the Swedish scenario can be seen in figure 4.4. For Poland, only the metals were assumed to be recycled. The ceramics and glass were assumed to be disposed of by landfill. The plastics, rubber and fluids were assumed to be disposed either by landfill or incineration. The assumptions related to end of life for Poland were made with the help of information from EU waste legislation [32]. As well as depending on the waste management treatments available in the database, a few of the material categories had a combination of disposal methods based on the region chosen. Meaning that assumptions for these material types were also based on the data availability while modelling in the software. For example, while modelling end of life for Polish scenario, the plastics were disposed of either by landfill or incineration depending on the type of plastic in the database. The assumptions made for the Polish scenario can be seen in figure 4.5.

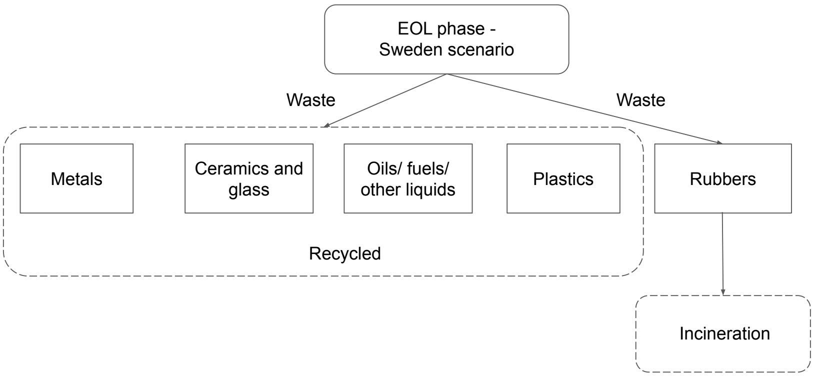


Figure 4.4: *End of life treatment for the material categories - Sweden*

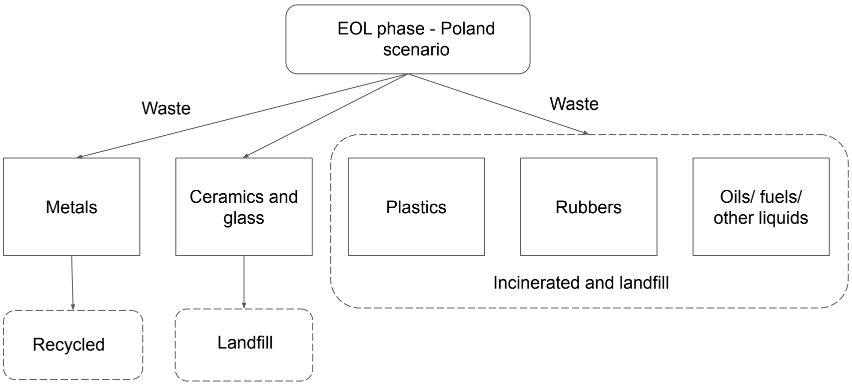


Figure 4.5: *End of life treatment for the material categories - Poland*

4.6 Sensitivity analysis - Application of what-if scenarios to the baseline

Four scenarios were evaluated in regards to sensitivity analysis. The first two scenarios were modelled in the sensitivity analysis and the next two scenarios included a literature study exploring alternative modifications to the life cycle. The first two modelled scenarios being the use of recycled aluminium and sourcing of material production in China. The next two scenarios covered by a literature study including the use of recycled steels and iron as well as use of recycled polyamides which is explained in sections 5.3.3 and 5.3.4.

4.6.1 Recycled aluminium

In order to model the use of recycled aluminium, aluminium scrap had to be implemented instead of primary aluminium. The existing aluminium product in the baseline model contained an aluminium ingot and additional energy needed for the high pressure die casting (HPDC). The process creating the aluminium ingot contained liquid aluminium which had to be replaced with aluminium scrap to represent recycled aluminium, see figure 4.6. A scrap that had been prepared for melting as well as energy to melt the scrap was added to the existing ingot production process in the database. With the output of the modified process being aluminium ingot from scrap content, the same energy for the casting process that was used for primary HPDC was applied to produce HPDC aluminium from scrap content.

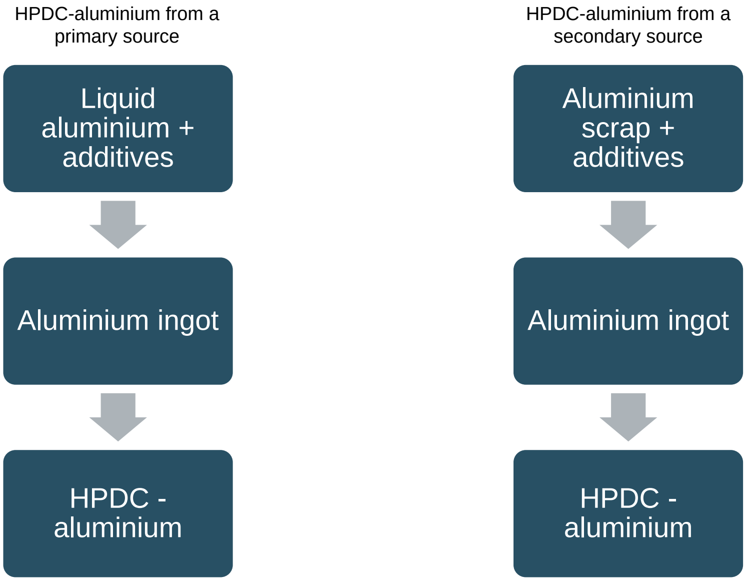


Figure 4.6: *A simplified diagram showing how the production of a recycled aluminium product differs from a primary aluminium product*

4.6.2 Material production sourcing

The assumption for baseline was that in regards to components both material production and refining took place near the supplier i.e mostly Europe. However, supply chains are often global where raw material production takes place in another part of the world than where the refining and consumption takes place. Hence, the sensitivity scenario aiming to explore the variations in the impacts based on location changes for the material production was analysed. Since Aurobay have a production site in China, the scenario aimed to model the raw material production in the Asian Pacific region. Material production processes that were available in APAC (Asia-Pacific) countries were chosen and otherwise global processes were applied. The data used in the model is listed in appendix A.1.

5

Results and discussion

The following chapter shows the results from the study, displays impacts of the chosen impact categories and different user scenarios. Results of the sensitivity analysis are presented and the results will be interpreted and discussed. The baseline model

5.1 Impact assessment

Seven impact categories were chosen and the LCA results for each impact category are presented in figure 5.1. The results are divided based on phases of the life cycle where the impacts occur. The results are relative and all impacts in each category make up for 100%. This helps identifying where in the life cycle the biggest impact takes place. Since the model includes credits for recycling, the impact from materials being recycled appears as a negative input, especially in the end of life phase where most of the waste treatment takes place.

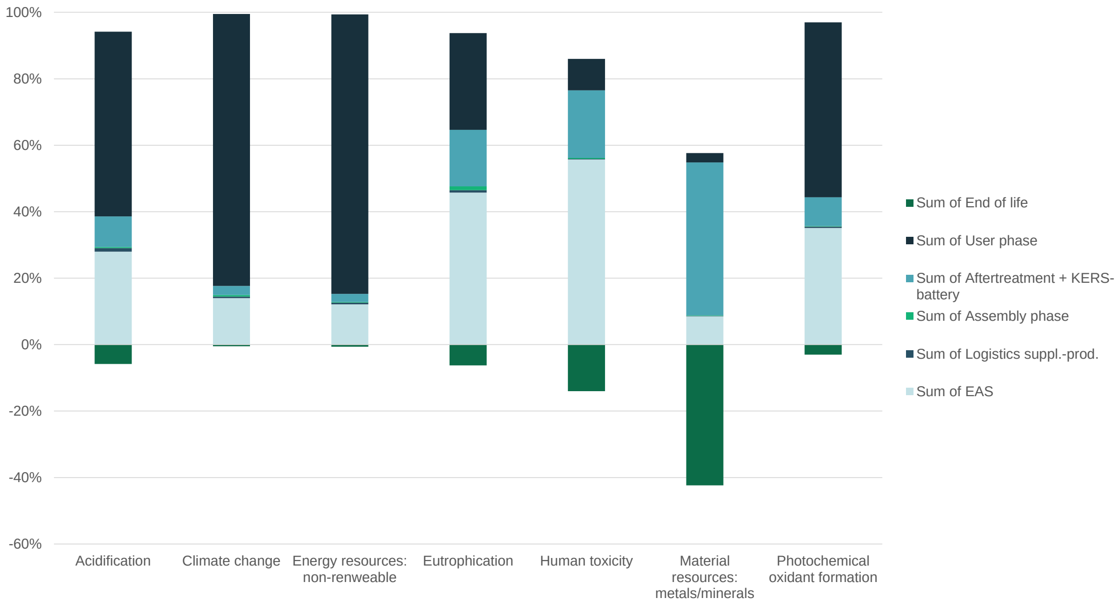


Figure 5.1: *Baseline analysis displayed over life cycle stages, Swedish scenario*

The results show that the use phase emissions creates the biggest impact in four of the seven impact categories. Acidification, climate change, energy resources and photochemical oxidant formation all have a majority of the impact in the use phase. The impacts from use phase are above 80% for climate change and energy resources. Both production and use of fossil fuels, as well as inputs from servicing and repairs are activities contributing to the impact. In these categories the second biggest impact comes from the manufacturing of components for the EAS together with the aftertreatment, KERS-battery and BISG.

The remaining impact categories; eutrophication, human toxicity and material resources are dominated by the production of components rather than use phase emissions. These categories are not much influenced by the production and use of fossil fuels, but more by the activities associated with raw material production and refining. Looking at material resources, extraction of raw materials from the earth crust leads to depletion of metals and minerals. The largest impact from material production can be attributed to the KERS-battery with the copper used in the graphite anode for the Li-ion battery having a high impact in the material resource category. This is also the case for the aftertreatment system and BISG which hold a larger share of copper compared to the EAS. Copper being one of the materials that generates a high impact from its mining and production process in this category. However, the materials with high contribution to the material resource category are to a large extent being recycled as seen in figure 5.1 with large credits for recycling.

The results also display the impact from inbound transport and the assembling phase which are represented by the "Sum of logistics supplier-prod" and the "Sum of Assembly phase" seen in figure 5.1. In the product life cycle of an engine, the impact from this particular phase becomes relatively small in comparison to other phases. Neither of the two phases extend and impact more than 1.3% of the total impacts for any impact category.

5.1.1 Comparison of impact results for Sweden and Poland scenarios

In order to assess how the location of the use phase and end of life affects the results, the two different use scenarios for Sweden and Poland were modelled. In figure 5.2, a comparison of the two scenarios can be seen. The higher fuel consumption together with less credits for recycling due to poorer waste management processes leads to a higher environmental impact for the Polish scenario. The impact is between 5-20% higher for the Polish scenario compared to the Swedish scenario. This difference was mainly because of the impact categories being dominated by use phase emissions and large credits for recycling that are affected.

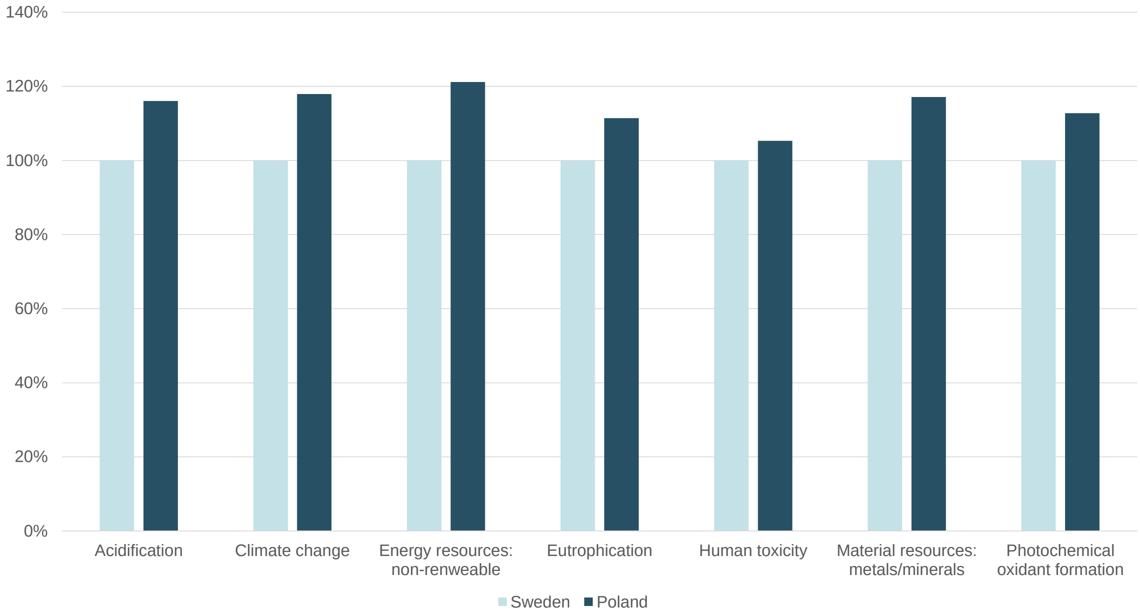


Figure 5.2: *Environmental impact for Swedish and Polish scenarios*

5.1.2 Impact results from component production

In regards to the impacts that occur before the user phase; the emissions from component production for EAS, aftertreatment system and KERS-battery were responsible for almost the entire impact. Hence the material and processing impacts for the different materials are displayed in figure 5.3. Here the material categories are further aggregated to see what type of materials have the biggest impact for the different impact categories.

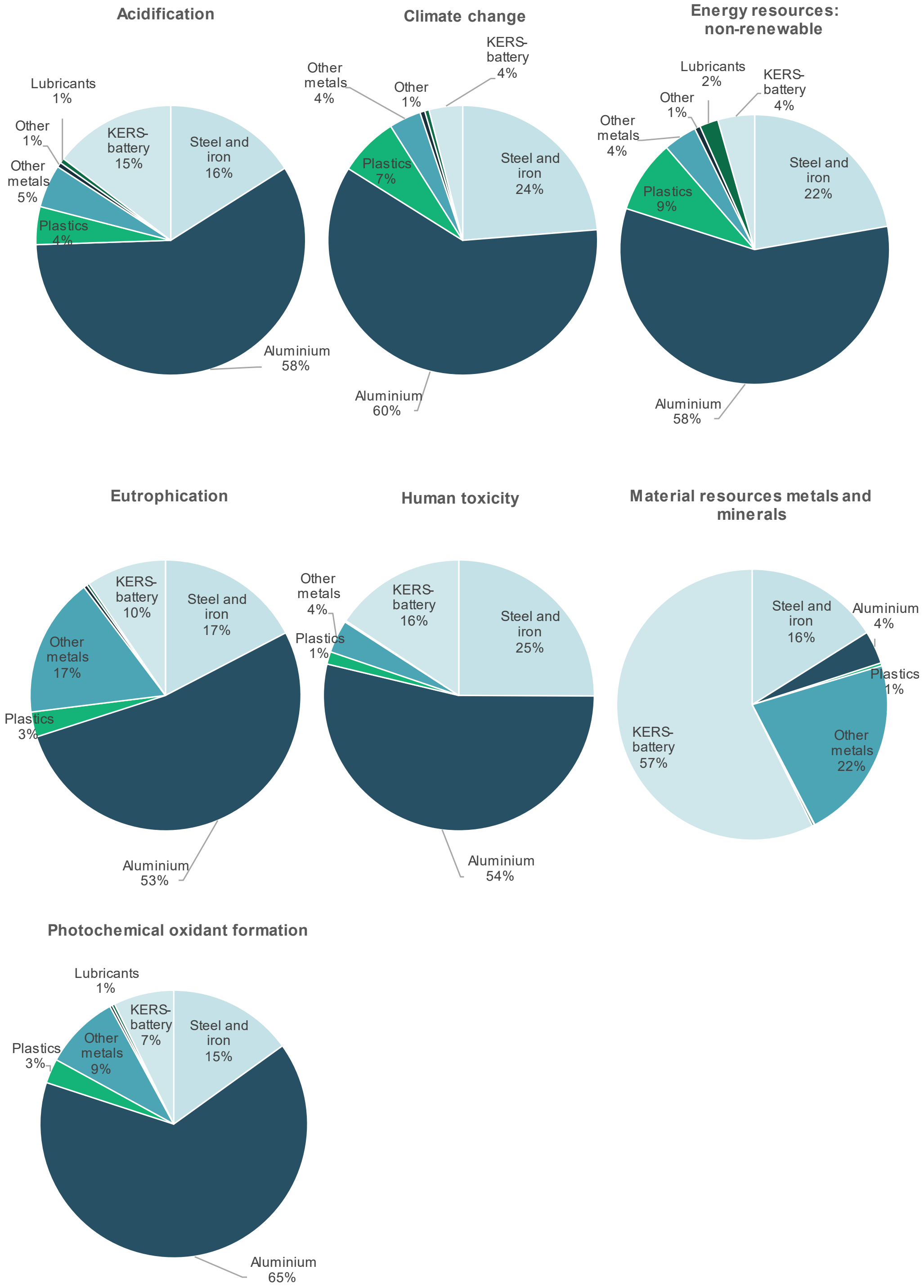


Figure 5.3: *Environmental impact for production of components displayed based on the material categories*

The results show the total impact for each material category and it's important to remember the material distribution by weight, shown in figure 4.1, where aluminium and steel are already the biggest category by weight. Nonetheless, the results clearly show that aluminium is the material responsible for the majority of the impacts in

6 out of 7 categories. It is known that aluminium is an energy intense material to produce, involving bauxite mining, alumina refining through electrolysis and casting [33].

Steels and iron are the second largest contributors with impacts between 16-24% depending on impact category. However it is worth noticing that by weight, the steels and iron make up 42% of the engine. Thus, it is has a relatively small impact compared to its weight.

Furthermore, the KERS-battery which is a Li-ion battery and the "other metals" which is mostly copper have relatively small impacts on climate change. This has been the impact category traditionally studied in LCA's within the automotive industry [14]. These two material categories have a significantly higher impact when the other impact categories are considered. Even though the KERS-battery and "other metals" only make up 5% and 2% respectively of the weight of the engine, they are heavy contributors in many impact categories. This indicates that insights of the actual impact of a material might get lost when only looking at global warming as these material would be seen as small contributors in that category.

5.2 Interpretation

As discussed in the results above, the use phase is the life cycle stage that has the biggest impact overall. This is the case even though only 8% of the emissions in the use phase has been allocated to the studied engine due to the weight allocation. If 100% would be allocated to the engine, then the impacts would increase as shown in figure 5.4.

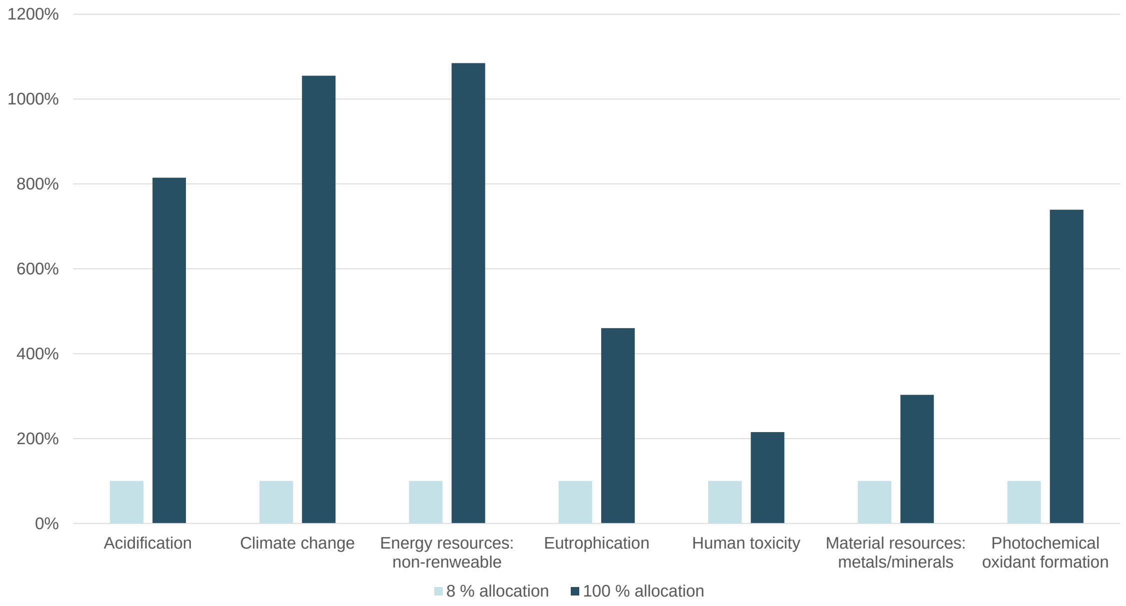


Figure 5.4: *The impact from the baseline model with 8% allocation in use phase compared to 100% allocation*

Looking at these results, the use phase impact becomes even more distinct as the difference from the 8% allocation solely belongs to the production and use of fossil fuel. Hence, exploring ways to reduce the environmental impact in the use phase is important to increase the sustainability of the product's life cycle. However, the fuel production is out of Aurobay's own operations. Therefore alternative scenarios in the use phase would require verification of impacts from production as well as consumption of alternative fuels. Also, there would be effects from these alternative scenarios on the engine design that would require further investigation. Hence, this study does not carry out any sensitivity analyses of the use phase with regards to fuels.

When looking at other emissions than the use phase emissions, upstream emissions from the production of components for the engine is the dominating contributor to the environmental impact. As 5.3 show, aluminium is the single largest contributor of the materials. Aluminium is also the most common material in the engine making it an important material. Furthermore it's a material with good characteristics for recycling and reuse [33]. The energy demand for producing aluminium from scrap is only 5% compared to the production of primary aluminium [33]. Due to lack of data availability on the share of recycled material in the product, only primary materials were used to model the life cycle. The sensitivity analysis therefore explores the potential usage of recycled aluminium.

Together with aluminium, steels and iron as well as plastics are the material categories with the biggest impact. The sensitivity analysis looks at recycling potentials for steel and iron. For plastics, polyamide was chosen since it was the plastic with the biggest environmental impact. In contrast to aluminium, recycled steels and polyamide were not modelled due to lack of data. Instead a literature study explored on how recycled content could reduce the environmental impact.

5.3 Sensitivity analysis

The first two scenarios modelled for the sensitivity analysis were the implementation of recycled aluminium and the alternative location of sourcing material production. These results will be presented below.

5.3.1 Recycled aluminium

Results in figure 5.5 shows the comparison of the baseline model compared to a model where 100% of the aluminium comes from scrap where the baseline in this case means 0% recycled aluminium in the model. By just changing the aluminium to a secondary source, the impact on global warming is reduced by 9% even though GWP is dominated by user phase emissions. The reduction of environmental impacts is even more significant for categories dominated by the components production with eutrophication and human toxicity being the most obvious ones with a reduction of 30% and 56% respectively.

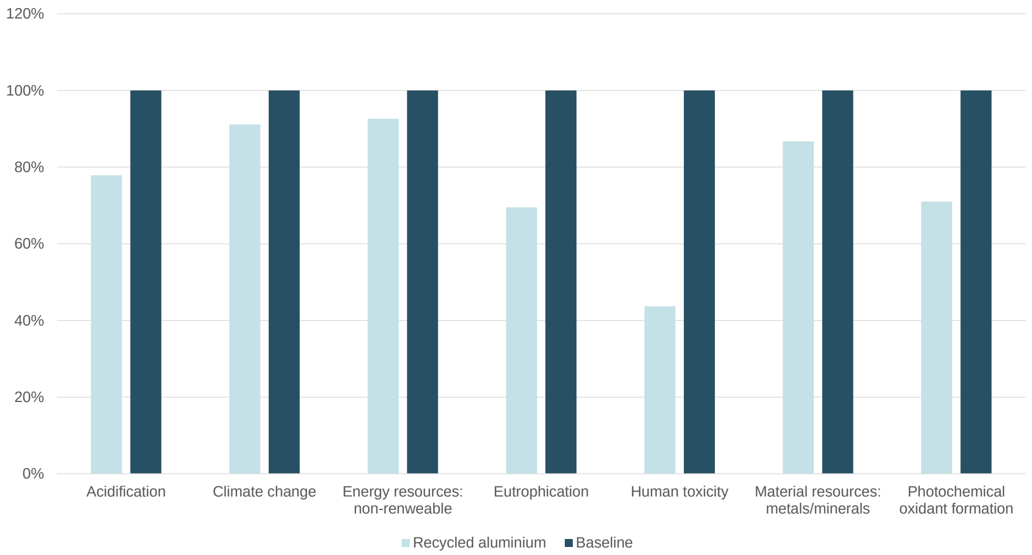


Figure 5.5: *Environmental impact of the engine for 100% recycled aluminium compared with 0% recycled aluminium in the engine*

Figure 5.6 displays how the impact is distributed on the phases and how it has changed when using 100% recycled aluminium compared to the baseline model. For climate change and energy resources, the magnitude of the phases in relation to each other is still similar whereas human toxicity changes making the aftertreatment system and KERS-battery the biggest impact phase. The biggest impact reduction using recycled aluminium lies mostly in the EAS where aluminium is more common compared to the aftertreatment system and KERS-battery.

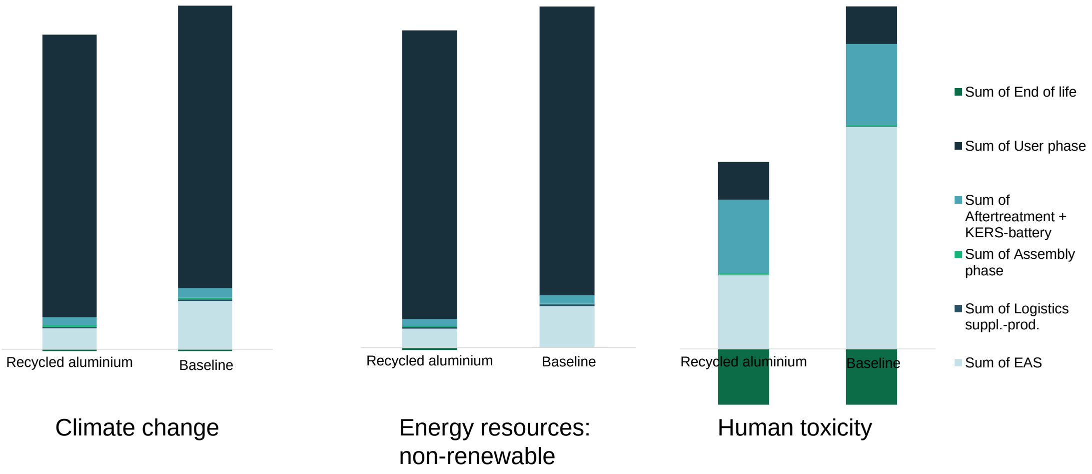


Figure 5.6: *Results for the life cycle stages with 100% recycled aluminium compared to the baseline model*

5.3.2 Material production sourcing

The other scenario in the sensitivity analysis that covered the material production and changes made with the location of the production were evaluated. The results of the comparison between European and Chinese sourcing are shown in figure 5.7. It can be seen that the Chinese sourcing generates a consistently higher environmental impact except for the human toxicity where the melting processes for aluminium are different between the European and Chinese sourcing. The melting processes for the European aluminium have a higher emission of polycyclic aromatic hydrocarbons than the Chinese sourcing which creates the increased human toxicity impact.

However, most affected are categories with a strong influence from the components production and refining with material resources and then acidification being the second largest increase, 73% and 56% respectively compared to the baseline model. Furthermore the two user phase dominated categories, climate change and energy resources are also facing an increase in impact, 22% and 13% respectively.

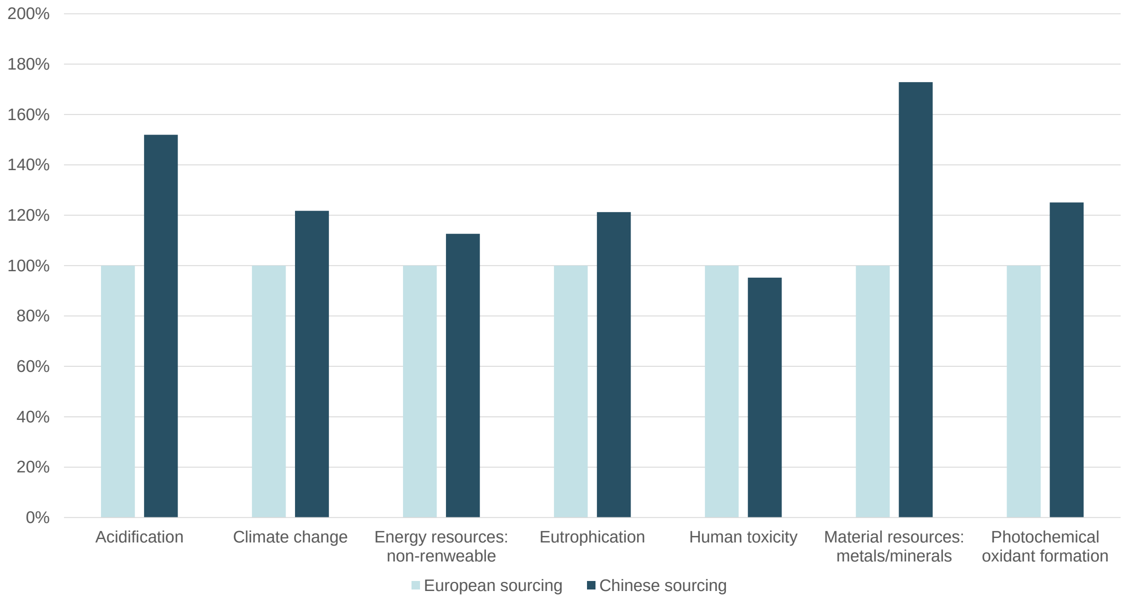
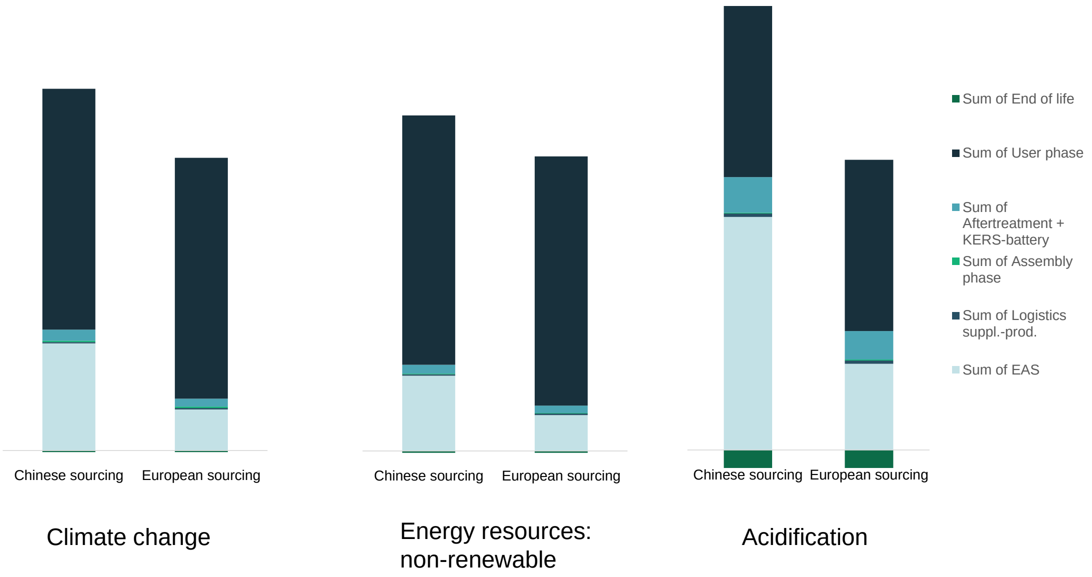


Figure 5.7: *Environmental impact for different locations of the material production*

Figure 5.8 displays the results for the different life cycle phases and clearly shows how the distribution of the impact changes. The impacts from both EAS and aftertreatment system along with KERS-battery are more than doubled for the Chinese sourcing when compared with the European sourcing.



Climate change

Energy resources: non-renewable

Acidification

Figure 5.8: *Results for the life cycle stages for different locations of the material production*

The results shows how much the impact can vary depending on the location of production. This can depend on the energy sources used, the treatment of emissions and hazardous waste, the efficiency and technology within the processes but also the treatment of wastes and reuse of waste materials in processes. Also metals and crude oil that has to be extracted from the ground can have different impacts depending on how these processes are handled in the different regions.

5.3.3 Recycled steel and iron

Steel and iron were the second highest impact contributor next to aluminium for almost 6 of the chosen impact categories except for the material resources category. It was seen that steel and iron contributed to impact of about 16 to 24% respectively as seen in the figure 5.3. Hence, it becomes important to look into other possibilities to reduce this impact. Therefore a literature study was performed as a part of sensitivity analysis to identify the benefits of using recycled steel and iron into the production replacing the virgin materials to attain environmental benefits.

Steel is a material that could be easily recycled which would reduce the need of virgin steel during production [34]. The steel industry is looking for possibilities that could incorporate recycled steel at the end of life of steel for achieving circular economy [34]. It was seen that a recycling methodology performed in accordance with the ISO standard 14040:2006 or 14044:2006 uses recycled scrap steel replacing the primary steel material during production [34]. It was also seen that with 1 kg of recycled scrap steel, a savings of about 1.5 kg CO_2 emissions along with 1.4 kg iron ore and 13.4 MJ primary consumption of energy was achieved when implementing the recycling methodology [34].

According to another source, it was seen that steel was an extensively recyclable material because of its capability to regain the intrinsic properties that it possess even after the use phase [35]. It was also seen that steel recycling rate accounts for about 30% of the global crude steel produced in total [35]. This source shows that recycled steel leads to a savings of energy and reduced CO_2 emissions/ unit of output depending on the cleaner energy mix being used [35].

Thus these study results emphasise the importance of replacing virgin steel with recycled steel during production for achieving savings on amount of materials extracted and mined, reduced waste thereby promoting circular economy with included environmental benefits like reduced pollution, reduced usage of resources etc.

5.3.4 Recycled polyamide

Plastics were generally not a high impact material category, however for the GWP and energy resource depletion, plastics made up for 7% and 9% respectively as seen in figure 5.3. Polyamide was the plastic with the highest overall impact which is why it was studied more in detail in the sensitivity analysis. The results of the literature study covered the possibilities and benefits of using recycled polyamide.

A life cycle assessment on the production of diesel fuel filter housing from recycled polyamide 6.6 that was used in airbags mapped the impact reductions in comparison to filters from primary polyamide 6.6 [36]. The study concluded that GHG-emissions were reduduced by 32% and the cumulative energy demand by 54%. Results from that study indicates a significant benefit from the use of recycled polyamide 6.6.

Polyamide is also a material with good characteristics for recycling, making it an interesting material for increased use of secondary material [37]. However, the methods for recovering and recycling has included complex systems that have caused higher costs. In comparison to aluminium where the metal can just be remelted after some processing, polyamide goes through a chemical process to de-polymerise the material which is the more expensive method. The method seen as more economically sustainable is the mechanical recycling where multiple methods can be used to prepare the material before being melt and injection molded [37].

A polyamide producer in the automotive industry working with Aurobay are producing polyamide 6 and 6.6 from recycled content. They state that a reduction of up to 9 kg of CO_2 and 1.5 kg of crude oil is achieved per kg of produced polyamide [38]. One should be careful about comparing results from different life cycle assessments as the assumptions can vary a lot. However this would indicate a reduction of almost 50% in CO_2 compared to the result of producing primary polyamide 6.6 in this study. The used material is being shredded multiple times before being regrinded into flakes and melted to a compound and extruded. Hence the use of mechanical recycling is used also in the production of polyamides used in the automotive industry.

As discussed above, the production of polyamides from a primary source generates a high impact in global warming potential creating an interest for increased recycled content. Studies also show that reductions can be achieved with recycled content in the polyamide production. The material is also highly recyclable, the challenge lies in making it profitable and achieve a secure supply to the volumes needed.

6

Conclusion

The goal was to create a baseline model for the life cycle of the engine and assess its environmental impact as well as analyse potential what if scenarios. The study has given insight into the life cycle impact of an ICE and looked beyond climate change by including multiple impact categories. It has shown Aurobay where in their product's life cycle the largest impact lies and how changes in the life cycle can affect the total impact.

Firstly the study confirms earlier studies regarding the dominance of the user phase impacts. Most of the impacts for categories affected by the use of fossil fuels originates from the user phase. The user phase impact is responsible for more than 80% for GWP and energy resources. By modelling different scenarios in the user phase and showing how the allocation of use phase related impacts affects the result, this study shows how the impact results varies depending on the use phase assumptions. Modelling different user phase scenarios and assessing user phase allocation shows the effect that assumptions in the user phase has on the impact. Also materials with energy intense manufacturing processes such as aluminium has the largest impact from components in these categories.

Aluminium components are responsible for most of the impacts from components. However, the inclusion of multiple impact categories also exposed other materials as big polluters with the KERS-battery and copper in focus. For acidification, eutrophication, human toxicity and material resources, these material categories have a large impact even though they make up for a small share of the engine's weight.

Furthermore the benefits of implementing recycled content to the material production were assessed by conducting a sensitivity analysis. The results show that the benefits from using recycled aluminium are substantial and an increase of circularity in the material sourcing is highly beneficial. The second sensitivity analysis gave insights on the importance of the material production location where the same product can have quite different environmental impacts depending on where it was being produced. It emphasises the importance of choosing where products are being sourced with care and knowing where a company's supply chain operates.

6.1 Recommendations

This study was the first complete life cycle assessment ever done by Aurobay and by this study, a baseline model was created. To increase both the level of detail and the level of accuracy in the model, the following recommendations for future work are presented.

6.1.1 Data availability and modeling

While conducting the study it became clear that the material database Ecoinvent often didn't contain the exact material that was desired and other activities had to approximate the actual activity. It would therefore be interesting to include multiple databases as a way to reduce the need for approximate activities.

As a way to further increase the accuracy of the model, getting data on the share of recycled content for the different materials as well as working with suppliers to gain more knowledge on the locations of material production would be important. In general, working closely with the suppliers to get primary data on the upstream processes could reduce the number of assumptions needed.

In order to increase traceability and facilitate implementation of the results within R&D at Aurobay, it is recommended that components could be aggregated based on function groups or parts in the engine. This way it would be easier to see the environmental impact for specific parts of the engine rather than material groups.

6.1.2 Further analysis

The study was able to display what processes had the biggest impacts for the different impact categories. However, it could add value to assess the magnitude of the environmental impact categories and the environmental effects that the engine has over a life cycle. As the current results show each impact category relative to its own total impact, no indication of the magnitude of each impact category is given to compare the effects from environmental impact categories with each other.

To improve the life cycle impact, making efforts to reduce the user phase emissions is of interest since it holds the majority of the impacts for most of the impact categories. This aspect was excluded in the study but looking on how alternative fuels would affect the life cycle impact could provide valuable insights for Aurobay's future strategy and planning.

Finally, a study on understanding the environmental impacts of the KERS-battery further would be recommended. For example, analysing the manufacturing location and types of KERS-batteries but also analyse the size of the battery. This could be done by modelling the relationship between the impacts from production and the benefits from fuel savings in the user phase to see what size the battery should have in order to have the smallest total impact over a life cycle.

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A

Appendix

A.1 Materials production and refining - dataset

Material	Material process	Region	China sourcing	Refining process	Region	Source
Aluminium alloy	aluminium, primary, ingot	IAI Area, EU27 & EFTA	CN	sheet rolling, aluminium	RER	Ecoinvent 3.8
	polyethylene, high density, granulate	RER	RoW	injection moulding	RER	Ecoinvent 3.8
Cast iron	cast iron	RER	RoW			Ecoinvent 3.8
Copper alloy	copper concentrate, sulfide ore	RoW	CN	wire drawing, copper	RER	Ecoinvent 3.8
	zinc sulfide	RER	RoW			Ecoinvent 3.8
Copper	copper concentrate, sulfide ore	RoW	CN	wire drawing, copper	RER	Ecoinvent 3.8
Galvanized steel	steel, unalloyed	RER				Ecoinvent 3.8
	zinc coat, pieces	RER				Ecoinvent 3.8
Aluminium	aluminium, primary, ingot	IAI Area, EU27 & EFTA	CN	HPDC(modelled)	HPDC(modelled)	Ecoinvent 3.8
High alloy steel	steel, chromium steel 18/8, hot rolled	RER	RoW	deep drawing, steel, 3500 kN press, automode	RER	Ecoinvent 3.8
High carbon steel	steel, unalloyed	RER	RoW	deep drawing, steel, 3500 kN press, automode	RER	Ecoinvent 3.8
				sheet rolling, steel	RER	Ecoinvent 3.8
Iron	iron pellet	RoW	IN	casting, steel, lost-wax	RoW	Ecoinvent 3.8
				deep drawing, steel, 3500 kN press, automode	RER	Ecoinvent 3.8
				sheet rolling, steel	RER	Ecoinvent 3.8
Low alloyed steel	steel, low-alloyed, hot rolled	RER	RoW	deep drawing, steel, 3500 kN press, automode	RER	Ecoinvent 3.8
Low carbon steel	steel, unalloyed	RER	RoW	sheet rolling, steel	RER	Ecoinvent 3.8
				deep drawing, steel, 3500 kN press, automode	RER	Ecoinvent 3.8
Medium carbon steel	steel, unalloyed	RER	RoW	sheet rolling, steel	RER	Ecoinvent 3.8
				deep drawing, steel, 3500 kN press, automode	RER	Ecoinvent 3.8
Nickel alloy	aluminium, primary, ingot	IAI Area, EU27 & EFTA	CN	forging, steel	RoW	Ecoinvent 3.8
	chromium	RER	RoW	sheet rolling, copper	RER	Ecoinvent 3.8

	copper concentrate, sulfide ore	RoW		CN			Ecoinvent 3.8
	nickel, class 1	GLO		GLO			Ecoinvent 3.8
	tungsten carbide powder	RoW		CN			Ecoinvent 3.8
Sintered steel	iron sinter	RER	**Sintered steel**	IN	casting, steel, lost-wax	RoW	Ecoinvent 3.8
					deep drawing, steel, 3500 kN press, automode	RER	Ecoinvent 3.8
Stainless steel	steel, chromium steel 18/8, hot rolled	RER	**Stainless steel**	RoW	deep drawing, steel, 3500 kN press, automode	RER	Ecoinvent 3.8
Steel	steel, unalloyed	RER	**Steel**	RoW	sheet rolling, steel	RER	Ecoinvent 3.8
					deep drawing, steel, 3500 kN press, automode	RER	Ecoinvent 3.8
Tool steel	steel, chromium steel 18/8, hot rolled	RER	**Tool steel**	RoW	deep drawing, steel, 3500 kN press, automode	RER	Ecoinvent 3.8
Zinc Nickel coating	nickel, class 1	GLO	**Zinc Nickel coating**	GLO	casting, brass	RoW	Ecoinvent 3.8
	zinc sulfide	RER		RoW	zinc coat, pieces	RER	Ecoinvent 3.8
Zinc	zinc sulfide	RER	**Zinc**	RoW	casting, aluminium, lost-wax	RoW	Ecoinvent 3.8
					sheet rolling, aluminium	RER	Ecoinvent 3.8
EPDM	synthetic rubber	RER	**EPDM**	RoW	injection moulding	RER	Ecoinvent 3.8
Elastomer	silicone product	RER	**Elastomer**	RoW	injection moulding	RER	Ecoinvent 3.8
Epoxy	epoxy resin, liquid	RER	**Epoxy**	RoW	injection moulding	RER	Ecoinvent 3.8
Fluoro rubber	polyvinylfluoride	US	**Fluoro rubber**	RoW	injection moulding	RER	Ecoinvent 3.8
Fluorosilicone	silicone product	RER	**Fluorosilicone**	RoW	injection moulding	RER	Ecoinvent 3.8
Lacquer	glass fibre reinforced plastic, polyamide, injection moulded	RER	**Lacquer**	RoW	extrusion, co-extrusion	RoW	Ecoinvent 3.8
					injection moulding	RER	Ecoinvent 3.8
PBT	polyethylene terephthalate, granulate, amorphous	RER	**PBT**	RoW	injection moulding	RER	Ecoinvent 3.8
PE	polyethylene, high density, granulate	RER	**PE**	RoW	injection moulding	RER	Ecoinvent 3.8
					extrusion, co-extrusion	RoW	Ecoinvent 3.8
PET	polyethylene terephthalate, granulate, bottle grade	RER	**PET**	RoW	injection moulding	RER	Ecoinvent 3.8
PP	polypropylene, granulate	RER	**PP**	RoW	injection moulding	RER	Ecoinvent 3.8
					extrusion, co-extrusion	RoW	Ecoinvent 3.8
PPA	glass fibre reinforced plastic, polyamide, injection moulded	RER	**PPA**	RoW	injection moulding	RER	Ecoinvent 3.8
					extrusion, co-extrusion	RoW	Ecoinvent 3.8
PPE	polyphenylene sulfide	GLO	**PPE**	GLO	injection moulding	RER	Ecoinvent 3.8
					extrusion, co-extrusion	RoW	Ecoinvent 3.8
PPS	polyphenylene sulfide	GLO	**PPS**	GLO	injection moulding	RER	Ecoinvent 3.8
					extrusion, co-extrusion	RoW	Ecoinvent 3.8
PTFE	polyvinylfluoride	GLO	**PTFE**	RoW	injection moulding	RER	Ecoinvent 3.8
					extrusion, co-extrusion	RoW	Ecoinvent 3.8

PUR	polyurethane, rigid foam	RER	**PUR**	RoW	injection moulding	RER	Ecoinvent 3.8
Polyamide	glass fibre reinforced plastic, polyamide, injection moulded	RER	**Polyamide**	RoW	extrusion, co-extrusion	RoW	Ecoinvent 3.8
	nylon 6-6	RER		RoW			Ecoinvent 3.8
Polyester	glass fibre reinforced plastic, polyester resin, hand lay-up	RER	**Polyester**	RoW	injection moulding	RER	Ecoinvent 3.8
Polymer composite	polypropylene, granulate	RER	**Polymer composite**	RoW	injection moulding	RER	Ecoinvent 3.8
					extrusion, co-extrusion	RoW	Ecoinvent 3.8
Rubber	synthetic rubber	RER	**Rubber**	RoW	injection moulding	RER	Ecoinvent 3.8
Silicone	silicone product	RER	**Silicone**	RoW	injection moulding	RER	Ecoinvent 3.8
Adhesive	polyurethane adhesive	GLO	**Adhesive**	GLO			Ecoinvent 3.8
Aluminosilicate	aluminium oxide, non-metallurgical	IAI Area, EU27 & EFTA	**Aluminosilicate**	CN	injection moulding	RER	Ecoinvent 3.8
	silicone product	RER		RoW			Ecoinvent 3.8
Ceramic glass	stucco	RoW	**Ceramic glass**	RoW			Ecoinvent 3.8
	sanitary ceramics	RoW		RoW			Ecoinvent 3.8
Ceramic	stucco	RoW	**Ceramic**	RoW			Ecoinvent 3.8
	sanitary ceramics	RoW		RoW			Ecoinvent 3.8
Cordierite	aluminium, primary, ingot	RoW	**Cordierite**	CN			Ecoinvent 3.8
	iron pellet	RoW		IN			Ecoinvent 3.8
	magnesium	RoW		CN			Ecoinvent 3.8
	silicone product	RER		RoW			Ecoinvent 3.8
Electrolyte	electrolyte, copper-rich	GLO	**Electrolyte**	GLO			Ecoinvent 3.8
Glass fabric	glass fibre	RER	**Glass fabric**	RoW	glass fibre reinforced plastic, polyamide, injection moulded	RER	Ecoinvent 3.8
Glass	glass fibre	RER	**Glass**	RoW	glass fibre reinforced plastic, polyamide, injection moulded	RER	Ecoinvent 3.8
Lubricant	lubricating oil	RER	**Lubricant**	RoW			Ecoinvent 3.8
Paper	paper, woodfree, coated	RER	**Paper**	RoW			Ecoinvent 3.8
Magnet	magnetite	GLO	**Magnet**	GLO	casting, aluminium, lost-wax	RoW	Ecoinvent 3.8
					deep drawing, steel, 650 kN press, automode	RoW	Ecoinvent 3.8
					sheet rolling, aluminium	RER	Ecoinvent 3.8
Activated carbon	activated carbon, granular	RER	**Activated carbon**	RoW			Ecoinvent 3.8
Graphite	graphite	RER	**Graphite**	RoW			Ecoinvent 3.8
KERS-battery	battery cell, Li-ion	GLO	**Graphite**	GLO			Ecoinvent 3.8

A.2 Inbound logistics - dataset

From suppliers to cross-dock and production plant					
From	**To**	**Transport mode**	**Distance(km)**	**Volumes(kg)**	**Ton*km**
Austria	Jirny	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Germany	Herne	Confidential	Confidential	Confidential	Confidential
	Maintal	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Turkey	Jirny	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
France	Desteldonk	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
China	Skövde	Confidential	Confidential	Confidential	Confidential
		Confidential	Confidential	Confidential	Confidential
		Confidential	Confidential	Confidential	Confidential
		Confidential	Confidential	Confidential	Confidential
Hungary	Jirny	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Switzerland	Desteldonk	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Netherlands	Desteldonk	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Spain	Desteldonk	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Czech Republic	Jirny	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Sweden	Gothenburg	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Poland	Skövde	Confidential	Confidential	Confidential	Confidential
	Jirny	Confidential	Confidential	Confidential	Confidential
	Gothenburg	Confidential	Confidential	Confidential	Confidential
Romania	Jirny	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Italy	Desteldonk	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Portugal	Desteldonk	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Slovakia	Jirny	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Bulgaria	Jirny	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential

Japan	Skövde	Confidential	Confidential	Confidential	Confidential
Norway	Skövde	Confidential	Confidential	Confidential	Confidential
Croatia	Jirny	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Great britain	Gothenburg	Confidential	Confidential	Confidential	Confidential
	Skövde	Confidential	Confidential	Confidential	Confidential
Thailand	Skövde	Confidential	Confidential	Confidential	Confidential
Estonia	Gothenburg	Confidential	Confidential	Confidential	Confidential
Belgium	Skövde	Confidential	Confidential	Confidential	Confidential
Serbia	Skövde	Confidential	Confidential	Confidential	Confidential
Latvia	Gothenburg	Confidential	Confidential	Confidential	Confidential

From cross-dock to production plant					
From	**To**	**Transport mode**	**Distance(km)**	**Volume(kg)**	**Ton*km**
Jirny	Skövde	Confidential	Confidential	Confidential	Confidential
Herne	Skövde	Confidential	Confidential	Confidential	Confidential
Maintal	Skövde	Confidential	Confidential	Confidential	Confidential
Desteldonk	Skövde	Confidential	Confidential	Confidential	Confidential
Gothenburg	Skövde	Confidential	Confidential	Confidential	Confidential

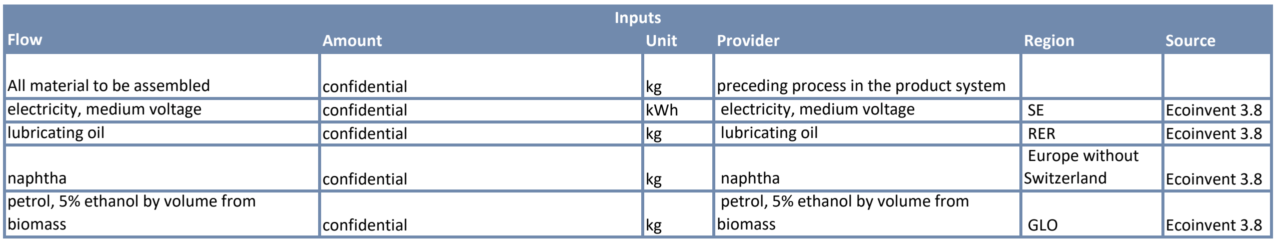
A.3 Transportation - dataset

Transportation - suppliers to production plant					
Flow	**Amount**	**Unit**	**Provider**	**Region**	**Source**
transport, freight, aircraft, unspecified	Confidential	ton*km	transport, freight, aircraft, unspecified	GLO	Ecoinvent 3.8
transport, freight, lorry, unspecified	Confidential	ton*km	transport, freight, lorry, unspecified	RER	Ecoinvent 3.8
transport, freight, sea, container ship	Confidential	ton*km	transport, freight, sea, container ship	GLO	Ecoinvent 3.8

Transportation - production plant to customer					
Flow	**Amount**	**Unit**	**Provider**	**Region**	**Source**
transport, freight, lorry 16-32 metric ton, EURO6	Confidential	kg*km	transport, freight, lorry 16-32 metric ton, EURO6	RER	Ecoinvent 3.8

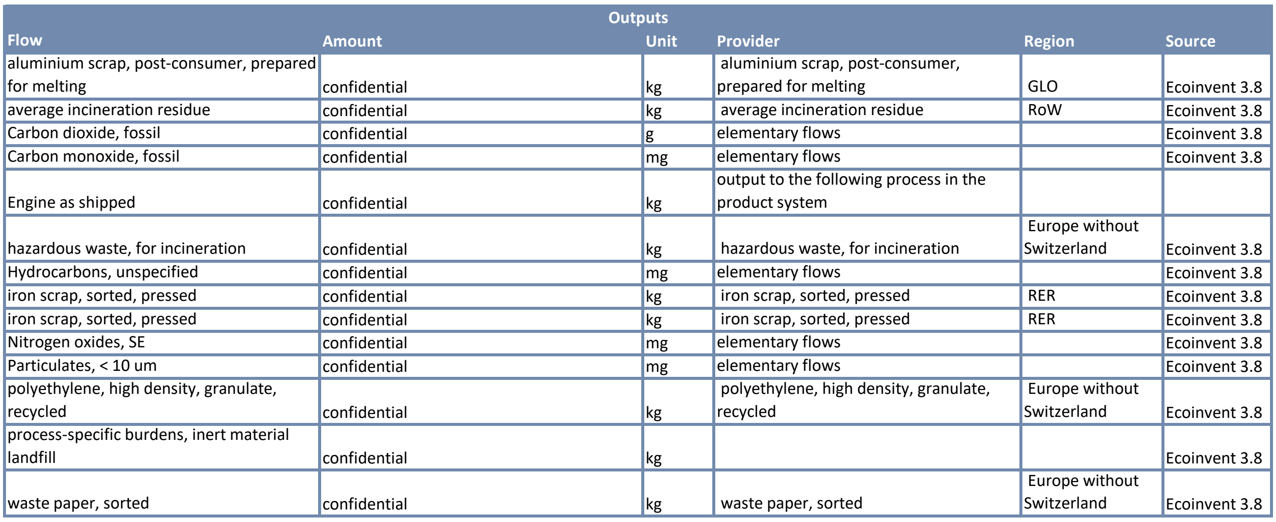
Transportation - customer to user(POL)					
Flow	**Amount**	**Unit**	**Provider**	**Region**	**Source**
transport, freight, lorry, unspecified	Confidential	kg*km	transport, freight, lorry, unspecified	RER	Ecoinvent 3.8
transport, freight, sea, ferry	Confidential	kg*km	transport, freight, sea, ferry	GLO	Ecoinvent 3.8

A.4 Skövde plant - dataset



Inputs

Flow	Amount	Unit	Provider	Region	Source
All material to be assembled	confidential	kg	preceding process in the product system		
electricity, medium voltage	confidential	kWh	electricity, medium voltage	SE	Ecoinvent 3.8
lubricating oil	confidential	kg	lubricating oil	RER	Ecoinvent 3.8
naphtha	confidential	kg	naphtha	Europe without Switzerland	Ecoinvent 3.8
petrol, 5% ethanol by volume from biomass	confidential	kg	petrol, 5% ethanol by volume from biomass	GLO	Ecoinvent 3.8



Outputs

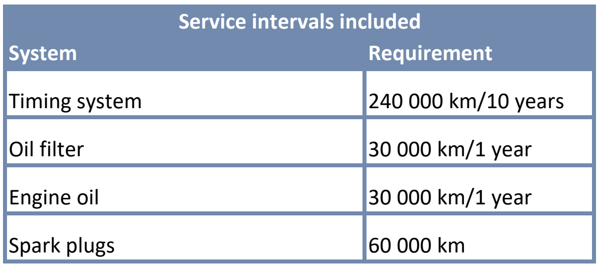
Flow	Amount	Unit	Provider	Region	Source
aluminium scrap, post-consumer, prepared for melting	confidential	kg	aluminium scrap, post-consumer, prepared for melting	GLO	Ecoinvent 3.8
average incineration residue	confidential	kg	average incineration residue	RoW	Ecoinvent 3.8
Carbon dioxide, fossil	confidential	g	elementary flows		Ecoinvent 3.8
Carbon monoxide, fossil	confidential	mg	elementary flows		Ecoinvent 3.8
Engine as shipped	confidential	kg	output to the following process in the product system		
hazardous waste, for incineration	confidential	kg	hazardous waste, for incineration	Europe without Switzerland	Ecoinvent 3.8
Hydrocarbons, unspecified	confidential	mg	elementary flows		Ecoinvent 3.8
iron scrap, sorted, pressed	confidential	kg	iron scrap, sorted, pressed	RER	Ecoinvent 3.8
iron scrap, sorted, pressed	confidential	kg	iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Nitrogen oxides, SE	confidential	mg	elementary flows		Ecoinvent 3.8
Particulates, < 10 um	confidential	mg	elementary flows		Ecoinvent 3.8
polyethylene, high density, granulate, recycled	confidential	kg	polyethylene, high density, granulate, recycled	Europe without Switzerland	Ecoinvent 3.8
process-specific burdens, inert material landfill	confidential	kg			Ecoinvent 3.8
waste paper, sorted	confidential	kg	waste paper, sorted	Europe without Switzerland	Ecoinvent 3.8

A.5 User phase - dataset

Inputs					
Flow	**Amount**	**Unit**	**Provider**	**Region**	**Source**
Engine in car	Confidential	kg	preceding process in the product system		
petrol, 5% ethanol by volume from biomass	8,15*0,75*3500*weight allocation	kg	petrol, 5% ethanol by volume from biomass	GLO	Ecoinvent 3.8
Recycling and waste - user phase	Confidential	kg	preceding process in the product system		
Transported - repaired and serviced parts	Confidential	kg	preceding process in the product system		

Outputs					
Flow	**Amount**	**Unit**	**Provider**	**Region**	**Source**
Carbon dioxide, fossil	180*350000*weight allocation	g	elementary flows		Ecoinvent 3.8
Carbon monoxide, fossil	294,2*350000*weight allocation	mg	elementary flows		Ecoinvent 3.8
Hydrocarbons, unspecified	14,6*350000*weight allocation	mg	elementary flows		Ecoinvent 3.8
Nitrogen oxides, SE	24,4*350000*weight allocation	mg	elementary flows		Ecoinvent 3.8
Particulates, < 10 um	0,23*350000*weight allocation	mg	elementary flows		Ecoinvent 3.8
Used engine	Confidential	kg	output to the following process in the product system		

A.6 Service intervals



Service intervals included	
System	**Requirement**
Timing system	240 000 km/10 years
Oil filter	30 000 km/1 year
Engine oil	30 000 km/1 year
Spark plugs	60 000 km

A.7 End of life - dataset

Material	Sweden	Region	Poland	Region	Source
Activated carbon	treatment of spent activated carbon with mercury, underground deposit	DE	treatment of spent activated carbon with mercury, underground deposit	DE	Ecoinvent 3.8
Adhesive	market for waste polyurethane	SE	market for waste polyurethane	SE	Ecoinvent 3.8
Aluminium	market for aluminium scrap, post-consumer, prepared for melting	GLO	market for aluminium scrap, post-consumer, prepared for melting	GLO	Ecoinvent 3.8
Aluminium alloy	market for aluminium scrap, post-consumer, prepared for melting	GLO	market for aluminium scrap, post-consumer, prepared for melting	GLO	Ecoinvent 3.8
Aluminosilicate	market for glass cullet, sorted	RER	market for glass cullet, sorted	RER	Ecoinvent 3.8
Cast iron	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Ceramic	market for glass cullet, sorted	RER	market for waste glass	PL	Ecoinvent 3.8
Ceramic glass	market for glass cullet, sorted	RER	market for waste glass	PL	Ecoinvent 3.8
Copper	market for bronze	GLO	market for bronze	GLO	Ecoinvent 3.8
Copper alloy	market for bronze	GLO	market for bronze	GLO	Ecoinvent 3.8
Cordierite	market for glass cullet, sorted	RER	market for glass cullet, sorted	RER	Ecoinvent 3.8
Elastomer	market for waste rubber, unspecified	Europe without Switzerland	market for waste rubber, unspecified	Europe without Switzerland	Ecoinvent 3.8
Electrolyte	market for bronze	GLO	market for bronze	GLO	Ecoinvent 3.8
EPDM	market for waste rubber, unspecified	Europe without Switzerland	market for waste rubber, unspecified	Europe without Switzerland	Ecoinvent 3.8
Epoxy	market for polyethylene, high density, granulate, recycled	Europe without Switzerland	market for waste polyethylene	PL	Ecoinvent 3.8
Fluoro rubber	market for waste polyvinylfluoride	RoW	market for waste polyvinylfluoride	RoW	Ecoinvent 3.8
Fluorosilicone	market for waste rubber, unspecified	Europe without Switzerland	market for waste rubber, unspecified	Europe without Switzerland	Ecoinvent 3.8
Galvanized steel	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Glass	market for glass cullet, sorted	RER	market for waste glass	PL	Ecoinvent 3.8
Glass fabric	market for glass cullet, sorted	RER	market for waste glass	PL	Ecoinvent 3.8
Graphite	treatment of spent activated carbon with mercury, underground deposit	DE	treatment of spent activated carbon with mercury, underground deposit	DE	Ecoinvent 3.8
High alloy steel	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8

High carbon steel	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Iron	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
KERS-battery	market for used Li-ion battery	GLO	market for used Li-ion battery	GLO	Ecoinvent 3.8
Lacquer	market for polyethylene, high density, granulate, recycled	Europe without Switzerland	market for waste polyethylene	PL	Ecoinvent 3.8
Low alloyed steel	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Low carbon steel	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Lubricant	Negative input	Negative input	market for bilge oil	Europe without Switzerland	Ecoinvent 3.8
Magnet	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Medium carbon steel	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Nickel alloy	market for aluminium scrap, post-consumer, prepared for melting	GLO	market for aluminium scrap, post-consumer, prepared for melting	GLO	Ecoinvent 3.8
Paper	treatment of waste paper, unsorted, sorting	Europe without Switzerland	market for waste graphical paper	PL	Ecoinvent 3.8
PBT	market for polyethylene, high density, granulate, recycled	Europe without Switzerland	market for waste polyethylene	PL	Ecoinvent 3.8
PE	market for polyethylene, high density, granulate, recycled	Europe without Switzerland	market for waste polyethylene	PL	Ecoinvent 3.8
PET	market for polyethylene terephthalate, granulate, amorphous, recycled	Europe without Switzerland	market for polyethylene terephthalate, granulate, amorphous, recycled	Europe without Switzerland	Ecoinvent 3.8
PGM	treatment of automobile catalyst	RER	treatment of automobile catalyst	RER	Ecoinvent 3.8
Polyamide	market for polyethylene, high density, granulate, recycled	Europe without Switzerland	market for waste polyethylene	PL	Ecoinvent 3.8
Polyester	market for polyethylene, high density, granulate, recycled	Europe without Switzerland	market for waste polyethylene	PL	Ecoinvent 3.8
Polymer composite	market for polyethylene, high density, granulate, recycled	Europe without Switzerland	market for waste polyethylene	PL	Ecoinvent 3.8

PP	market for polyethylene, high density, granulate, recycled	Europe without Switzerland	market for waste polyethylene	PL	Ecoinvent 3.8
PPA	market for glass cullet, sorted	RER	market for waste glass	PL	Ecoinvent 3.8
PPE	market for polyethylene, high density, granulate, recycled	Europe without Switzerland	market for waste polyethylene	PL	Ecoinvent 3.8
PPS	market for polyethylene, high density, granulate, recycled	Europe without Switzerland	market for waste polyethylene	PL	Ecoinvent 3.8
PTFE	market for waste polyvinylfluoride	RoW	market for waste polyvinylfluoride	RoW	Ecoinvent 3.8
PUR	market for waste polyurethane foam	RoW	market for waste polyurethane	PL	Ecoinvent 3.8
Rubber	market for waste rubber, unspecified	Europe without Switzerland	market for waste rubber, unspecified	Europe without Switzerland	Ecoinvent 3.8
Silicone	market for waste rubber, unspecified	Europe without Switzerland	market for waste rubber, unspecified	Europe without Switzerland	Ecoinvent 3.8
Sintered steel	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Stainless steel	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Steel	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Tool steel	market for iron scrap, sorted, pressed	RER	market for iron scrap, sorted, pressed	RER	Ecoinvent 3.8
Zinc	treatment of zinc in car shredder residue, municipal incineration	RoW	treatment of zinc in car shredder residue, municipal incineration	RoW	Ecoinvent 3.8
Zinc Nickel coating	treatment of zinc in car shredder residue, municipal incineration	RoW	treatment of zinc in car shredder residue, municipal incineration	RoW	Ecoinvent 3.8

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