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TAMPERE UNIVERSITY OF TECHNOLOGY

VIIVI ROUHENTO

MANUFACTURING OF A NON-ROAD DIESEL ENGINE FROM THE LIFE CYCLE PERSPECTIVE

Master of Science Thesis

Examiner: prof. Jukka Rintala
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ABSTRACT

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The goal of this study was to identify and quantify the environmental impacts produced during the life cycle of a tractor's diesel engine with the life cycle assessment (LCA) method. Furthermore, the goal was to recognize which life cycle stages impact the environment the most. Opportunities to reduce environmental impacts were also examined. The focus of this study was on the manufacturing of the engine due to the intended audience of the study, the engine manufacturer AGCO Power.

LCA of the diesel engine was performed using SimaPro software and the chosen environmental impact method was the ILCD Midpoint 2011+ method. The examined environmental impact categories were climate change, eutrophication (land, fresh water and ocean), acidification, photochemical ozone formation, ozone depletion and mineral, fossil and renewable resource depletion. The life cycle stages of the of the engine included in the study were raw material extraction and production, manufacturing, distribution, use and end-of-life stages. Data related to input and output flows of unit processes were collected from the engine manufacturer, the producers and suppliers of materials, waste handlers and the tractor manufacturer and the distributor. Some data was also obtained from the EcoInvent database and literature.

The environmental impact results showed that the use of the diesel engine produced most of the environmental impacts in each impact category. The engine manufacturer is able to influence the environmental impact of the use stage by technical means, which they have already done in obligation to the Directive 97/68/EC. However, the environmental impacts of the use stage could also be reduced by using renewable diesel instead of conventional. Though, the type of fuel used in the engine is up to the user of the tractor and cannot be influenced by the engine manufacturer. After the use stage, the greatest environmental impacts rose from the extraction and production of raw materials. Distribution, end-of-life and manufacturing stages each accounted less than one percent of environmental impact results in each category. Distribution and end-of-life stages, however, had a greater impact on all other impact categories, except on climate change and freshwater eutrophication, compared to the manufacturing stage.

In the diesel engine manufacturing stage, the greatest environmental impacts came indirectly and directly from the use of electricity, heat and chemicals. The study found that by purchasing renewable energy, the environmental impact of the manufacturing stage could be reduced. The environmental impact of chemical use could be reduced by installing suitable treatment systems into processes and by better optimization of production processes, thus reducing the consumption of chemicals.

TIIVISTELMÄ

VIIVI ROUHENTO: Työkoneen dieselmoottorin valmistuksen ympäristövaikutukset elinkaarinäkökulmasta
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Tässä työssä tavoitteena oli tunnistaa ja laskea traktorin dieselmoottorin elinkaaren eri vaiheiden aiheuttamat ympäristövaikutukset elinkaarianalyysimenetelmällä. Tavoitteena oli myös tunnistaa ne elinkaaren vaiheet ja niihin sisältyvät prosessit, jotka kuormittavat ympäristöä eniten. Lisäksi työssä selvitettiin erilaisia keinoja vähentää moottorin elinkaaren aikana syntyneitä ympäristövaikutuksia. Pääpaino työssä oli moottorin valmistusvaiheella, koska työ tehtiin yhteistyössä dieselmoottorin valmistajan kanssa ja he olivat tämän työn kohdeyleisö.

Dieselmoottorin elinkaarianalyysi tehtiin SimaPro ohjelmistolla ja karakterisointiin käytettiin ILCD 2011 Midpoint+ metodia. Tutkitut ympäristövaikutusluokat olivat ilmastonmuutos, rehevöityminen (maa, makea vesi ja meri), happamoituminen, otsonin muodostuminen, otsonikato ja luonnonvarojen ehtyminen. Tutkimukseen sisällytettiin seuraavat elinkaaren vaiheet: raaka-aineiden louhinta ja tuotanto, moottorin valmistus, jakelu, käyttö ja loppusijoituksen vaiheet. Lähtötiedot kerättiin moottorin valmistajalta, materiaalien tuottajilta ja toimittajilta, traktorin valmistajalta ja jakelijalta sekä jätteiden käsittelijöiltä. Osa lähtötiedoista kerättiin EcoInvent tietokannasta ja kirjallisuudesta.

Tulokset osoittivat, että dieselmoottorin käyttövaihe tuotti suurimman osan elinkaaren aikana syntyvistä ympäristövaikutuksista jokaisessa vaikutuskategoriassa. Dieselmoottorin valmistaja pystyy vaikuttamaan käyttövaiheen ympäristövaikutuksiin teknisin keinoin ja näin he ovatkin tehneet päästödirektiivin (direktiivi 97/68/EY) siivittämänä. Käyttövaiheessa fossiilisen polttoaineen vaihtaminen uusiutuvaan dieseliin vähentäisi käytön ympäristövaikutuksia. Dieselpolttoaineen valinta on kuitenkin täysin traktorin käyttäjän päätös, eikä moottorin valmistaja voi siihen vaikuttaa. Käyttövaiheen jälkeen suurimmat ympäristövaikutukset syntyivät raaka-aineiden louhinnasta ja tuotannosta. Jakelun, loppusijoituksen ja moottorin valmistuksen ympäristövaikutukset muodostivat jokainen alle prosentin osuuden ympäristövaikutuskategorioista. Jakelulla ja loppusijoituksella oli kuitenkin suurempi vaikutus ympäristöön kuin moottorin valmistuksella kaikissa muissa vaikutuskategorioissa, paitsi ilmastonmuutos- ja makean veden rehevöitymisen vaikutuskategorioissa.

Dieselmoottorin tuotannossa suurimmat ympäristövaikutukset syntyivät sähkön, lämmön ja kemikaalien käytöstä. Työssä todettiin, että ostamalla uusiutuvaa sähkö- ja lämpöenergiaa, tuotannon ympäristövaikutuksia voitaisiin pienentää. Kemikaalien käytöstä johtuvia ympäristövaikutuksia voitaisiin pienentää asentamalla erilaisia käsittelyjärjestelmiä prosesseihin sekä optimoimalla tuotannon prosessit paremmin. Tällöin kemikaalien kulutuskin vähenisi.

PREFACE

This study was conducted in collaboration with AGCO Power and I would like to thank them for this interesting and current topic. I would also like to thank everyone at AGCO Power who helped me in any way during this process, especially Aija Koivuranta, Juha Randell and Petri Kivelä. A big thank you to my examiner, Professor Jukka Rintala from Tampere University of Technology for actively guiding me through the process and giving valuable feedback when needed.

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Tampere, June 3rd 2018

Viivi Rouhento

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LIST OF SYMBOLS AND ABBREVIATIONS

FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standards
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
RF	Radiative forcing

CO_2	Carbon dioxide
CO	Carbon monoxide
CH_4	Methane
HC	Halocarbons
N_2H	Nitrogen dioxide
NO_x	Nitrogen oxides
NH_4^+	Ammonium ion
NH_3	Ammonia
NMVOC	Non-methane volatile organic compound
O_3	Ozone
PA	Polyamide
PAH	Polycyclic aromatic hydrocarbons
PC	Polycarbonate
POP	Persistent organic pollutants
SO_2	Sulphur dioxide
SO_x	Sulphur oxides
VOC	Volatile organic compound

1. INTRODUCTION

Vast concern on the environmental threats against our planet has woken up the automotive industry to take part in reducing environmental impacts among the rest of the world. With the latest scandal concerning diesel powered vehicles, referred as the "Dieselgate", the need to assess all environmental impacts produced by the automotive industry and reassessing the policies regarding these environmental impacts, is an issue of present interest (Brand 2016; Zachariadis 2016). Emission directives, such as European Stage (I-V) standards for non-road machinery and Euro standards (1-6) for road vehicles have been set to control the exhaust gases produced by the combustion of diesel fuel (DieselNet a, b). However, controlling the amount of exhaust gases is not the only way to reduce environmental impacts of a fuel powered vehicle or a machine.

By improving and implementing a full environmental management system to the organization, the environmental performance of the company and its products can be improved (Hartmann & Vachon 2018). Life cycle assessment (LCA) method is a type of environmental management tool. With LCA, emissions produced during the life cycle of a product are recognized and further reduced. (SFS-EN ISO 14040 2006) A product, such as a diesel-powered vehicle with its engine, has a reputation of being one of the most polluting products in the world. Hence, reducing only exhaust emissions from fuel combustion is not the only way to enhance the environmental performance and image of a diesel-powered vehicle and its engine.

With LCA, environmental impacts produced during the life cycle of a good or a service, referred as a product, are recognized and quantified. Life cycle of a product usually starts from the raw material acquisition and ends in the end-of-life functions. Identifying the life cycle stages of the product is only a small part of the LCA process. All life cycle stages require input and output flows which are quantified in the assessment. Input flow refers to energy and natural resources while output flow refers to produced waste and emissions. LCA is a standardized process. ISO 14040 "Environmental management. Life cycle assessment. Principles and framework" and ISO 14044 "Environmental management. Life cycle assessment. Requirements and guidelines" set the framework for LCA. The LCA process is divided into four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation. (SFS-EN ISO 14040 2006)

Here an LCA study was conducted for a non-road (tractor) diesel engine according to the ISO 14040 and 14044 standards. The study was done in collaboration with the engine manufacturer, AGCO Power. AGCO Power is certifying into ISO 14001:2015 standard “Environmental management system. Requirements with guidance for use”. In this ISO 14001 standard, one of the demands is to recognize the environmental impacts caused by their product during its life cycle (SFS-EN ISO 14001 2015). The objectives of this study were to estimate and calculate the magnitudes of the environmental impacts produced during the life cycle of a four-cylinder diesel engine of a tractor. In addition, the goal was to recognize which stages in the life cycle cause the highest impacts on the environment and how AGCO Power could reduce these impacts.

Chapter 2 presents the theory of LCA in the ISO 14040 and ISO 14044 standards. Chapter 3 explains basic structure and operation principle of the diesel engine. Moreover, chapter 3 presents the theory of all life cycle stages in the engine’s life cycle and discusses the relevant environmental impacts caused by these stages. Chapter 4 presents materials and methods used in the study including the scope of the study. Chapter 5 presents the main data and assumptions made in the collected data for the calculations. The calculated environmental impact results produced during the life cycle of the studied diesel engine are presented in chapter 6. Chapter 7 discusses and interprets the results presented in the previous chapter. In this chapter recommendations to reduce the environmental impacts of the diesel engine are made. Chapter 8 draws conclusions from the conducted study.

2. LIFE CYCLE ASSESSMENT

In life cycle assessment (LCA) method, environmental impacts caused by a product during its life cycle are assessed. A product refers to any goods or services. A life cycle of a product starts from the raw material acquisition and ends in the final disposal of the product. LCA is a useful tool for decision makers to identify environmental impacts caused by their product and hence, further improve the sustainability performance of the product. LCA can also be utilized in decision making, product development and marketing. (SFS-EN ISO 14040 2006)

2.1 Methodology

There are two standards available regarding the LCA method published by The International Organization for Standards (ISO):

1. SFS-EN ISO 14040 (2006): *Environmental management. Life cycle assessment. Principles and framework.*
2. SFS-EN ISO 14044 (2006): *Environmental management. Life cycle assessment. Requirements and guidelines.*

LCA studies are usually conducted according to these standards. LCA method is divided into four main phases (SFS-EN ISO 14040 2006):

1. Goal and scope definition
2. Life cycle inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)
4. Interpretation

These four phases create the framework for LCA. LCA is an iterative process, implicating that the four phases are linked together forming iterative loops (Fig. 1). For example, the scope and goal phase is defined in the beginning of the study. However, after gaining more accurate knowledge on certain processes or discovering that required data is not available, the initial scope needs to be reconsidered which may cause changes in all phases after the goal and scope phase. (ILCD 2010)

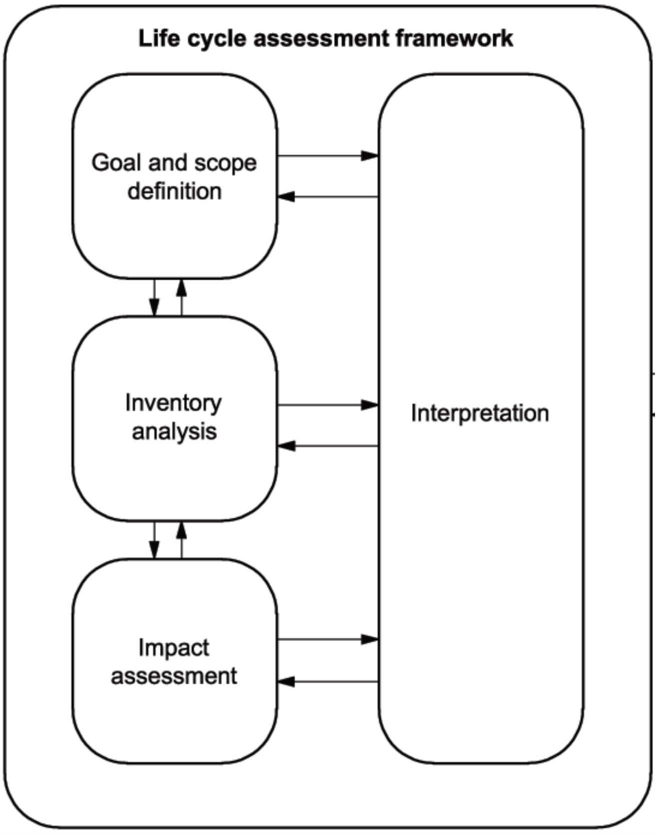


Figure 1. *The four phases of LCA and their connections to each other (SFS-EN ISO 14040 2006).*

Life cycle of a product usually starts from the design and development stage and goes through production, use and end-of-life functions, such as reuse and recycling processes (Fig. 2). In addition, different life cycle stages form loops with each other. For example, after the product is used it can be recycled into a remanufactured product and be sent back into use. Each of these life cycle stages require input flows, such as energy and natural resources, and produce output flows, such as emissions to air and water. Hence each life cycle stage impacts the environment. (Rebitzer et al. 2004) Developing a comprehensive structure or a chart portraying the life cycle of the studied product, with its input and output flows, is a key tool in conducting an LCA and a practical way to start the first phase of the assessment which is the goal and scope phase.

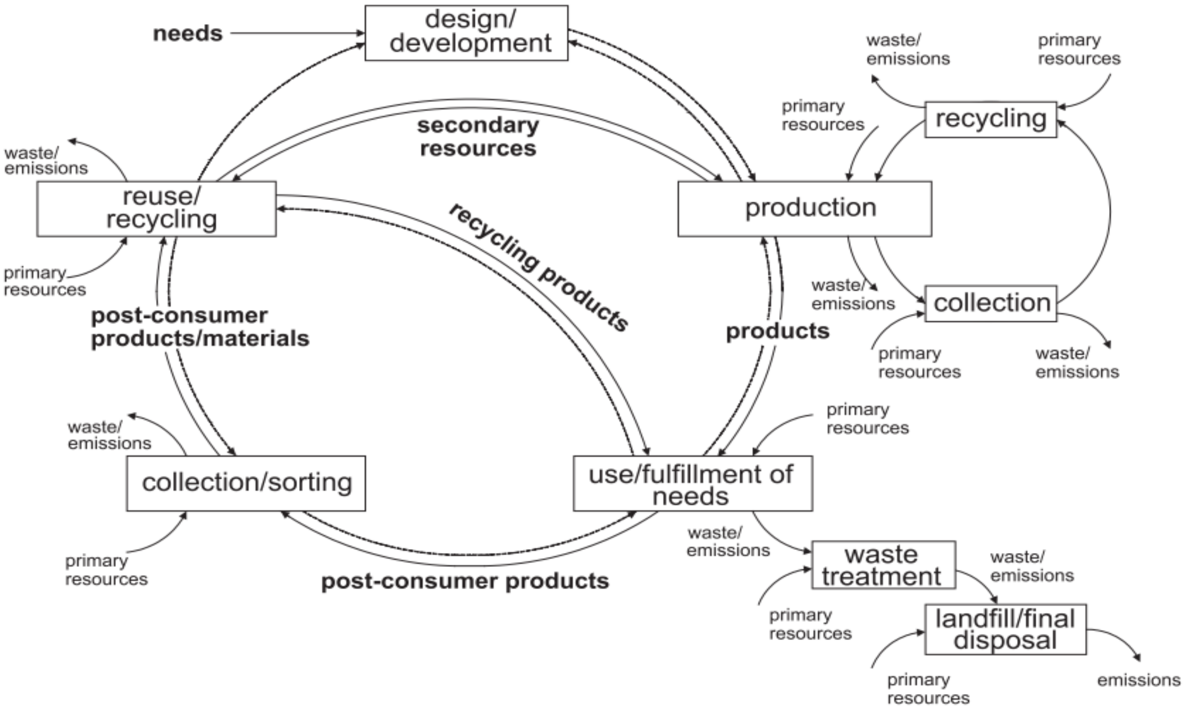


Figure 2. *An example life cycle of a product (Rebitzer et al. 2004).*

2.2 Goal and Scope Definition

In the first phase of the LCA method, the goal of the study is set, and scope is defined. The goal of LCA clarifies reasons for conducting the study, the intended application of the study and the audience. The goal should be well presented and consistent with the intended application of the study. When defining the scope, the following should be determined: product systems and unit processes, the functional unit, system boundaries, allocations, relevant environmental impact categories and life cycle impact assessment methodology, assumptions, chosen interpretation method, requirements for data and its quality, value choices and limitations. (SFS-EN ISO 14044 2006)

A product system in scope definition refers to the complete life cycle with all input and output flows within the system. Unit process in turn, refers to phases within the product system, such as raw material extraction or distribution. The functional unit is a quantitative reference which serves as a tool in quantifying all input and output data, thus ensuring that product systems can be compared. (SFS-EN ISO 14044 2006) For example, if the life cycle of a glass bottle and a plastic bottle containing juice are compared, the functional unit could be “one serving of juice”. Then all input and output flows of product systems are defined per one serving of juice providing the results in the same unit. This way results regarding glass and plastic bottles can be compared. Defining the functional unit is one of the most important steps in the goal and scope phase. However, determining the right functional unit can be difficult since there is no definite correct solution (Reap et al. 2008). Some products have multiple functions and the key is to choose the most relevant one (Hischier & Reichart 2003). In addition to choosing the right functional unit and implementing it to each function can be challenging. Especially when dealing with functions that are difficult to quantify. (Cooper 2003)

System boundary of the study defines which unit processes are included in the LCA. The chosen boundaries need to be justified and consistent with the goal. Additionally, the depth in which unit processes are examined, is defined. Only unit processes should be included or excluded from the system boundary, meaning that neither life cycle stages nor input or output flows should be used as parameters in creating boundaries. (SFS-EN ISO 14040 2006) Choosing system boundary is important, since too narrow boundary may not reflect reality. In the worst case scenario, incorrect results may lead to wrongful interpretations and decisions. (Reap et al. 2008)

2.3 Life Cycle Inventory Analysis

The goal and scope phase gives the required frames to perform a life cycle inventory analysis (LCI). In LCI, data is gathered, and preliminary calculations are made. For example, production of aluminum requires energy and aluminum oxides (input flows) and produces aluminum and emissions to air (output flows) (Fig. 3). These input and output flows, referred as data, have to be quantified. The data is collected for all unit processes within the system boundaries. Gathered data is considered to be primary data when it is collected from the source, from the manufacturer or the distributor for example. In the absence of primary data, data can be collected as secondary data from literature. (SFS-EN ISO 14040 2006)

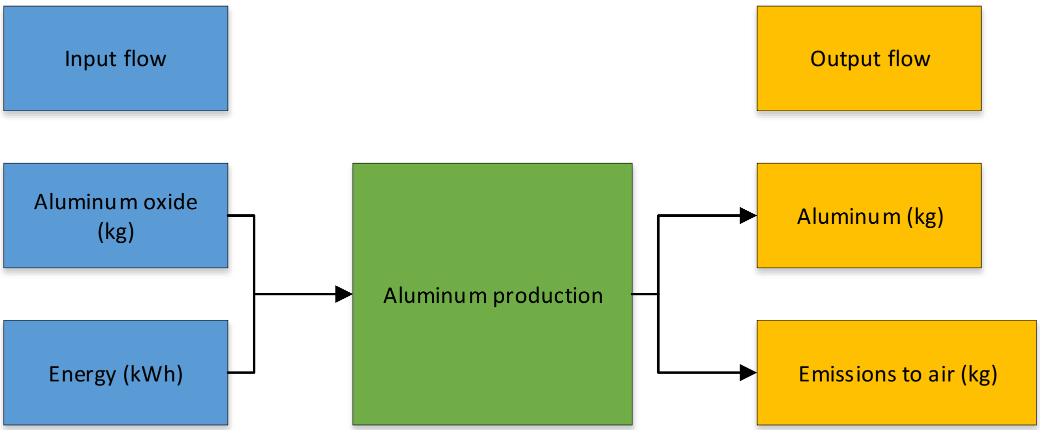


Figure 3. *An example of a unit process, aluminum production, with its input and output flows.*

The collected data has to be validated and related to the reference flow of the functional unit. For example, in aluminum production the functional unit could be “kg of produced aluminum”. Then the data would be defined as “kWh per kg of produced aluminum,” or “kg of aluminum oxide per kg of produced aluminum”, for example. In order to quantify emissions, emissions factors need to be collected as primary or secondary data. Emissions can be calculated with the following equation (NAEI 2007):

$$Emissions = Activity\ data * Emission\ factor, \tag{1}$$

where activity data refers to the acquired input flow for a unit process. The calculated emission value is then further needed in the life cycle impact assessment phase.

When a unit process has multifunctional purpose, allocations need to be made in order to divide emissions for single products. (SFS-EN ISO 14040 2006) Allocation can be made for example with a physical allocation or with an economic allocation method. In the physical allocation method, the emissions produced are allocated to products by mass, and in economic allocation they can be allocated by cost or profits gained. (Ponsioen)

2.4 Life Cycle Impact Assessment and Interpretation

Life cycle impact assessment (LCIA) phase calculates and estimates the impacts on the environment by using the data collected in the LCI phase. LCIA is divided into obligatory and optional elements. Obligatory elements are (SFS-EN ISO 14040 2006):

1. Selection of impact categories, category indicators and characterization models
2. Assignment of LCI (classification)
3. Calculation of category indicator results (characterization).

Environmental impacts can be divided into three areas of protection: human health, natural environment and natural resources. These areas of protection contain endpoint categories: damage to human health, damage to ecosystem diversity and resource scarcity which can further be divided into midpoint categories (Fig. 4). In a midpoint category, the chosen indicator is between emissions and endpoints in the cause-effect chain. For example, carbon dioxide is an emission contributing to climate change (midpoint category), which causes damage to ecosystem diversity at the end of the impact pathway (endpoint category). In general, the results for midpoint categories are more accurate than results for the endpoints. (ILDC 2010) Chapter 2.5 presents some of the commonly used environmental impact categories more specifically. After selecting the impact method, with its impact categories, category indicators and characterization models, the results from LCI are assigned into the chosen impact categories (classification).

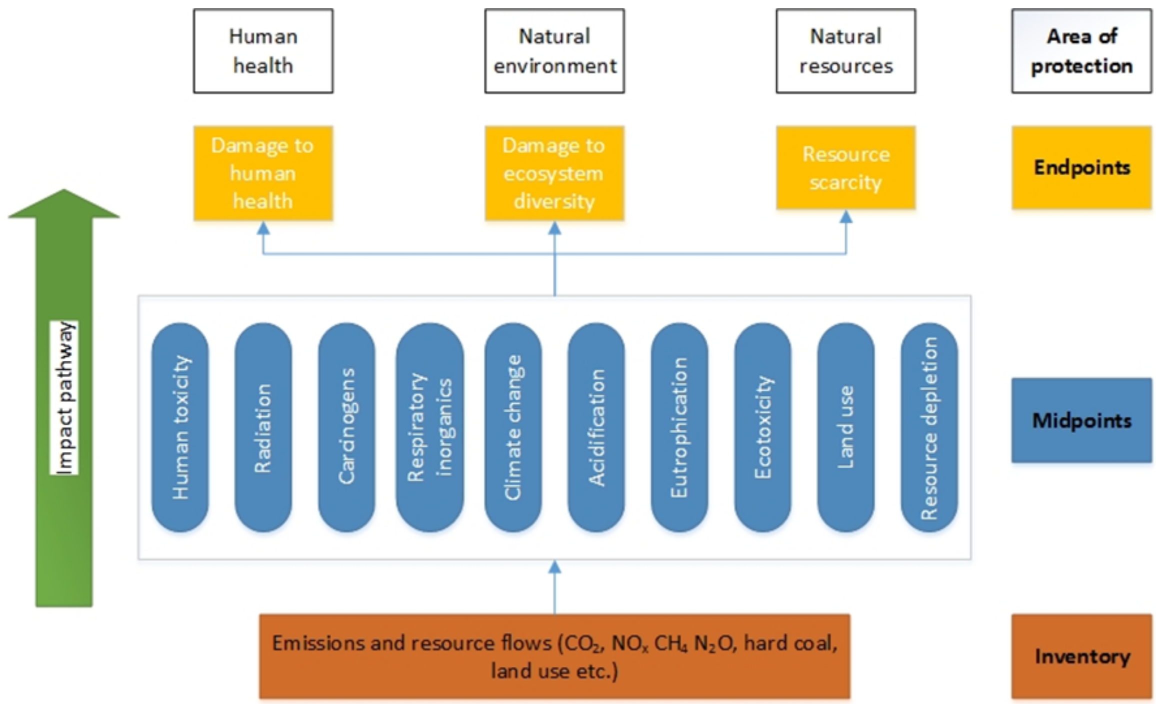


Figure 4. *A schematic way to present the LCIA phase (Modified from ILDC 2010).*

After classification, LCI results are converted into common units by using pointed characterization factors, and combined within the assigned impact category. (SFS-EN ISO 14040 2006) This is done with the following equation:

$$I_i = \sum_j C_{i,j} E_j, \tag{2}$$

where I_i is the chosen impact category's indicator result, $C_{i,j}$ is the characterization factor for the indicator j of the impact category i, and E_j is the quantity of the indicator j (Seppälä 2004).

From obligatory elements, environmental impact results are gained. In addition, normalization, grouping and weighting can be done after obligatory elements are completed. (SFS-EN ISO 14040 2006) In normalization, the results are compared to some reference value, such as one person's impact on climate change in one year, giving the results some perspective (Ponsioen 2014). Grouping refers to a process where the results are sorted or ranked, for example based on priority. In weighting the normalization results are multiplied with weighing factors. The weighting results implicate relative importance of the environmental impact results. Performing these optional phases may help to compare the environmental impacts of different products to each other. (Curran 2012)

Finally, the interpretation phase evaluates the results of LCI and LCIA phases. Results can be interpreted with the following three steps (SFS-EN ISO 14040 2006):

1. Identification of the significant results in LCI and LCIA
2. Checking of sensitivity, consistency and overall completeness
3. Drawing of conclusions and making of recommendations.

Sensitivity analysis evaluates the certainty of collected data and calculated results and furthermore, recognizes limitations of the LCA work. Sensitivity analysis can be performed in LCI, LCIA, normalization and weighting phases. It identifies which focus points of the product system need to be revised, for example by further data collection. However, only focus points that have a strong impact on results should be considered in the revision and improvement work. (Groen et al. 2017; Hung & Ma 2009)

2.5 Impact Assessment Method and Impact Categories

There are several impact assessment methods developed for different impact categories. They differ from each other for example by the number of substances covered, characterization model used and software implementation. (Owsianiak et al. 2014) ILCD 2011 Midpoint+ method is developed by European Commission, Joint Research Centre. It combines impact assessment methods that are considered as best options to be used for a specific impact category, into one impact assessment method (Table 1). The quality of the impact methods are classified into three levels (I-III). Level I methods are "recommended and satisfactory", level II methods are "recommended but in need of some improvements" and level III methods are "recommended, but to be applied with caution". (ILCD 2011)

Even though the variety of environmental impact categories is large, global companies tend to choose the same categories for their LCA. 16 global companies chose more or less the following as relevant impact categories: energy consumption, climate change, acidification, eutrophication, material depletion, photochemical ozone formation, ozone depletion, waste problem, eco-toxicity, human toxicity and water reserve impact. In addition, land use and biodiversity where used as impact categories in two companies (Nygren & Antikainen 2010). The ISO 14040 standard might have affected the decisions since it provides latter mentioned categories as examples. However, choosing the same categories as everyone else might not reflect the actual environmental impacts that the examined product system causes during its life cycle. On the other hand, not all categories are easy to examine reliably.

Table 1. *Recommended impact methods at midpoint level by the European Commission, also known as ILCD 2011 Midpoint+ method (ILCD 2011).*

Impact category	**LCIA method (reference)**	**Indicator**	**Unit**		**Level**
Resource depletion, mineral, fossil and renewable	CML 2002 (Guinée et al. 2002)	Scarcity	kg Sb eq	kilograms of antimony equivalent	II
Resource depletion, water	Model for water consumption as in Swiss ecoscarcity (Frischknecht et al. 2008)	Water use related to local scarcity of water	m3 eq	cubic meters of water equivalent	III
Land use	Model based on Soil organic matter (Milá i Canals et al. 2007)	Soil organic matter	kg C deficit	kilograms of soil organic carbon deficit	III
Climate change	IPCC model for 100 years (IPCC 2013)	Radiative forcing as global warming potential (GWP_{100})	kg CO2 eq	kilograms of carbon dioxide equivalent	I
Acidification	Accumulated Exceedance (AE) (Seppälä et al. 2006; Posch et al. 2008)	Accumulated exceedance (AE)	mol H^+ eq	moles of hydrogen ion equivalent	II
Eutrophication, terrestrial	Accumulated Exceedance (AE) (Seppälä et al. 2006; Posch et al. 2008)	Accumulated exceedance (AE)	mol N eq	moles of nitrogen equivalent	II
Eutrophication, aquatic	EUTREND model as implemented in ReCiPe (Strujis et al. 2009)	Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N)	kg P eq / kg N eq	kilograms of phosphorous/nitrogen equivalent	II
Photochemical ozone formation	LOTOS-EUROS as applied in ReCiPe (Van Zelm et al. 2008)	Tropospheric ozone concentration increase	kg NMVOC eq	kilograms of non-methane volatile organic compounds equivalent	II
Ozone depletion	Steady-state ODPs 1999 (ILCD 2011)	Ozone depletion potential (ODP)	kg CFC-11 eq	kilograms of chlorofluorocarbon equivalent	I
Ecotoxicity, freshwater	USEtox model (Rosenbaum et al. 2008)	Comparative toxic unit for ecosystems	CTU_e	comparative toxic unit	II/III

Ecotoxicity, terrestrial and marine	No methods recommended				
Human toxicity, cancer effects	Usetox model (Rosenbaum et al. 2008)	Comparative toxic unit for humans	CTU_h	comparative toxic unit	II/III
Human toxicity, non-cancer effects	Usetox model (Rosenbaum et al. 2008)	Comparative toxic unit for humans	CTU_h	comparative toxic unit	II/III
Particulate matter	RiskPoll model (Rabl & Spadaro 2004)	Intake fraction for fine particles	kg PM2.5 eq	kilograms of particulate matter equivalent	I
Ionizing radiation, human health	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al. 2000)	Human exposure efficiency relative to U235	kg U^{235} eq	kilograms of uranium isotope 235 equivalent	II
Ionizing radiation, ecosystems	No methods recommended				

2.5.1 Climate Change

Global warming refers to human caused climate change, moreover to the rise in the Earth's temperature (IPCC 2014). The phenomenon contributing to the rising temperature is called the greenhouse effect. The Sun gives the Earth the power to maintain a climate-system by radiating energy. Part of this radiation is reflected back to space, while most of it is being absorbed by the atmosphere. From the absorbed radiation, some is reflected back to space, leaving approximately half of the original amount of radiation on Earth. This radiation is then emitted by Earth as infrared radiation, i.e. thermal radiation. Although some of this infrared radiation passes the atmosphere, most of it is being absorbed and re-emitted by clouds and greenhouse gases (GHG). Hence, the higher the GHG concentration in the air, the more infrared radiation stays inside the atmosphere, warming up the Earth. (IPCC 2007)

Greenhouse gases (GHG) are carbon dioxide (CO_2), methane (NH_4), nitrous oxide (N_2O) and halocarbons (HC) (IPCC 2007). Water vapor is also recognized as a contributor to the greenhouse effect, although the magnitude of this contribution divides opinions. Some studies argue that changes in stratospheric water vapor force climate change (Shindel 2001; Smith et al. 2001). While others question the magnitude of the effect due to the fact that current measurement techniques are not reliable enough (Solomon et al. 2010).

When examining the climate change impact category, either one or both of the following indicators are determined, radiative forcing (RF) and global warming potential (GWP). Natural and anthropogenic substances and processes change the Earth's energy budget. RF is a quantity which describes this change. Positive RF means that the Earth is not radiating as much energy back to space as it is receiving from the Sun. In other words, the Earth's temperature rises. If RF is negative, the Earth loses energy causing it to cool. The unit of RF is Watts per square meter (W/m^2). (IPCC 2014)

GWP is derived from RF. GWP allows comparing different climate forcing agents, such as GHGs, to each other. In GWP, GHGs are calculated as kg of carbon dioxide equivalent (kg CO_2 eq). GWP values can be presented in different time frames, such as 20, 50 and 100 years (Table 2). However, 100 years is the most commonly used time frame. The GWP values convert emissions as carbon dioxide equivalent, hence the GWP factor for CO_2 is 1. The GWP_{100} factor for CH_4 is 28. This means that CH_4 has 28 times higher effect on climate change, over a 100-year period of time, compared to CO_2. In other words, 1 kg of CH_4 emissions is equivalent to 28 kg of CO_2 emissions. (IPCC 2013)

Table 2. *Commonly used global warming potential values (GWP_{20}, GWP_{50}, GWP_{100}) (IPCC 2013).*

Greenhouse gas	Global warming potential$_{20}$ (kg CO_2 eq)	Global warming potential$_{50}$ (kg CO_2 eq)	Global warming potential$_{100}$ (kg CO_2 eq)
CO_2	1	1	1
CH_4	84	48	28
N_2O	264	276	265

2.5.2 Acidification

Acidifying compounds are sulphur oxides (SO_x), nitrogen oxides (NO_x) and ammonia (NH_3). The reaction products of these compounds cause changes in the chemical composition of the environment, such as acidification of soil and surface water. (Bordeau & Stanner 1995) Most of SO_x emissions come from the energy production. NO_x emissions come from road transportation and energy production. (Eurostat 2018) Most of NH_3 emissions come from agriculture, for example from manure management and cultivation of crops (Eurostat 2018; Jensen et al. 2007; Pirlo et al. 2016).

There are several methods to calculate the acidification impact. In the ILCD 2011 Midpoint+ method, impact on acidification is calculated with the accumulated exceedance method at midpoint in mol H^+ eq (Seppälä et al. 2006). Another popular method is the

CML method at midpoint, which calculates acidification potential in kg of SO_2 eq (Guinée et al. 2002, cit. Bach & Finkbeiner 2017). Accumulated exceedance method uses country-specific characterization factors for European countries while the CML method uses same characterization factors for European countries in general. However, the accumulated exceedance method considers only terrestrial acidification while the CML method takes into account marine and freshwater acidification as well. (Bach & Finkbeiner 2017) The accumulated exceedance method is recommended by the European Commission (ILCD 2011). Though, if the life cycle inventory includes emissions produced outside of Europe, the impact on acidification might be too high or low with both methods.

2.5.3 Eutrophication

Nutrients causing eutrophication are nitrogen (N) and phosphorous (P). Eutrophication refers to the phenomenon where the water body or soil is overloaded with these nutrients. Excess amount of nutrients causes many ecological impacts, such as change in biodiversity, species composition and emergence of toxic species in both aquatic and terrestrial ecosystems. In addition, growth in microbial biomass causes depletion in oxygen of the water body. (Dokkum et al. 2005) In addition, global warming intensifies eutrophication. For example, rise in temperature with excess amount of nutrients accelerates growth of harmful cyanobacteria. (O'Neil et al. 2012) Excess phosphorous and nitrogen are released to the soil or waterbody from runoffs of agriculture (HELCOM 2011).

Eutrophication impact category is usually divided into terrestrial, freshwater and marine eutrophication. In terrestrial and marine eutrophication, nitrogen compounds are limiting factors, hence considered in the inventory. The accumulated exceedance method calculates terrestrial eutrophication in mol N eq. The method accounts N, NH_3, nitrogen dioxides (NO_2), and NO_x emissions in the characterization factors (Seppälä et al. 2006). Marine eutrophication is assessed in the ReCiPe midpoint method. Emissions contributing to marine eutrophication in the ReCiPe method are NH_3, ammonium ions (NH_4^+), nitrate, nitrite, N, NO_2, NO and NO_x and the unit used is kg N eq (Bach & Finkbeiner 2017).

Phosphorous is considered as the limiting factor in freshwater systems, hence phosphorous compounds are considered in the inventory of freshwater eutrophication. Freshwater eutrophication is modelled by using the ReCiPe midpoint method in the ILCD 2011 Midpoint+ method. The ReCiPe method takes into account phosphate, phosphoric acid and phosphorous emissions to soil and waterbody. The unit used in the ReCiPe method is kg P eq. (Bach & Finkbeiner 2017)

2.5.4 Photochemical Ozone Formation and Ozone Depletion

The increase of ozone in the troposphere and depletion of ozone in the stratosphere are environmental issues. Ozone is formed by photochemical reactions caused by natural and anthropogenic precursors. About 90 % of Earth's ozone is in the stratosphere, while the remaining 10 % is in the troposphere. (Atmosphere-ABC 2017; EPA 2014) Ozone in the troposphere is an atmospheric emission which is created by the reaction of nitrogen oxides and volatile organic compounds (VOCs) in the presence of sunlight. Increased amount of ozone in the troposphere causes damage to human health and terrestrial ecosystems (EPA 2014). Together with ozone, NO_x and VOC emissions form photochemical smog, which is a serious health hazard in many cities, such as Beijing and Delhi (Griffiths 2016; IPCC 2001). The recommended impact assessment method for photochemical ozone formation is the ReCiPe method and the unit is kg NMVOC (non-methane volatile organic compounds) eq. There are 133 types of NO_x and NMVOC emissions assessed in the ReCiPe method for photochemical ozone creation (Van Zelm et al. 2008).

Unlike ozone in the troposphere, naturally occurring ozone in the stratosphere is necessary for life. It protects living cells against solar ultraviolet radiation. Hence, depletion of the stratospheric ozone is an environmental issue. Chlorofluorocarbons (CFC), methyl chloroform, carbon tetrachloride, hydrochlorofluorocarbons (HCFC), methyl chloride, methyl bromide and bromochloromethane are the main cause for ozone depletion. (Ozone Secretariat 2018) These compounds were emitted to air mainly from refrigerators, foam blowing, pharmaceutical- and chemical industry (Sarkar 2018). Today, only HCFCs are still effecting the ozone depletion increasingly, while the use of the rest of the substances have been phased out by the Montreal Protocol. (Ozone Secretariat 2018; WMO/UNEP 2014) For ozone depletion, the recommended method for modelling is the EDIP 2003 method and the unit used is kg CFC-11 eq. The EDIP 2003 method calculates the destructive effects on the stratospheric ozone layer over a time period of 100 years. Emissions covered in the method are all previously mentioned substances, totaling up to 23 different emissions. (ILCD 2011)

2.5.5 Mineral, Fossil and Renewable Resource Depletion

With LCA, scarce resources consumed during the life cycle of a product can be recognized and thus reduced or changed into more sustainable alternatives. Resources refers to abiotic and biotic resources and furthermore into fossil, renewable and mineral resources. Assessing the scarcity of a resource can be approach from different perspectives. Resource depletion can be evaluated for example as depletion of mass or energy, resource availability or as the future consequences of resource extraction. (Klinglmair et al. 2012)

The CML 2002 method is recommended by the ILCD 2011 Midpoint+ method and it evaluates the decreasing availability of resources. The CML 2002 method covers 184 resources which can be divided into fossil, renewable and mineral resources and energy from fossil and renewable resources (Table 3). The unit used in the CML 2002 method is kg Sb eq. (Guinée et al. 2002, cit. PRé-Sustainability 2018) Antimony is classified as one of the scarcest raw materials in the world based on the risk of supply shortage, which is followed by higher economic impact compared to other raw materials (European Commission 2017).

Table 3. *Resources covered in the CML 2002 method for mineral, fossil and renewable resource depletion impact category (Guinée et al. 2002, cit. PRé-Sustainability 2018).*

Type of resource		**Resources covered in the CML 2002 method**
Non-renewable, abiotic	**Energy**	Energy from coal, gas, oil, peat, pit methane, sulfur and uranium
	Fossil	Coal, gas, oil, peat
	Mineral	Aluminum, antimony, arsenic, barium, bauxite, beryllium, bismuth, boron, cadmium, cerium, chromium, cobalt, copper, dysprosium, erbium, europium, fluorspar, gadolinium, gallium, garnet, germanium, gold, holmium, indium, iodine, iron, lanthanum, lead, lithium, lutetium, magnesium, manganese, mercury, molybdenum, neodymium, nickel, niobium, palladium, perlite, phosphorous, platinum, potassium, praseodymium, rhenium, scandium, selenium, silver, sodium chloride, sodium sulfate, strontium, sulfur, talc, tantalum, tellurium, terbium, thallium, thulium, tin, titanium, tungsten, uranium, vanadium, vermiculite, ytterbium, zinc, zirconium
Renewable, biotic		Organic carbon in soil or biomass stock

3. DIESEL ENGINE AND ITS LIFE CYCLE

Rudolf Diesel invented a combustion engine in the 1890's, which set the beginning of the development of a modern-day diesel engine (Mollenhauer et al. 2010). Diesel engines are used in dozens of different types of vehicles and machinery, such as passenger cars, buses, cargo- and cruise ships, tractors and other farm machinery, trains, construction equipment, generators and trucks (Application of Diesel Engines; Mollenhauer et al. 2010).

A typical life cycle of an engine consists of raw material acquisition, transportation of materials, manufacturing, use and end-of-life functions (Fig. 5). Li et al. (2013) conducted an LCA on a diesel engine manufactured in China for trucks. They considered climate change, acidification, eutrophication and photochemical ozone formation impact categories in their study. Their results indicated that the usage stage in the engine's life cycle had the largest environmental impacts. Jiang et al. (2014) conducted LCA of a diesel engine using an integrated hybrid LCI model. They studied the produced amount of GHG, SO_2 and dust emissions, during the life time of an engine. Their study concluded too, that use stage in the life cycle of an engine had the largest impact on the environment. Liu et al. (2014) compared environmental impacts caused during the life cycle of an originally manufactured diesel engine to a remanufactured diesel engine. Sutherland et al. (2008) calculated how much energy is saved when an engine is remanufactured.

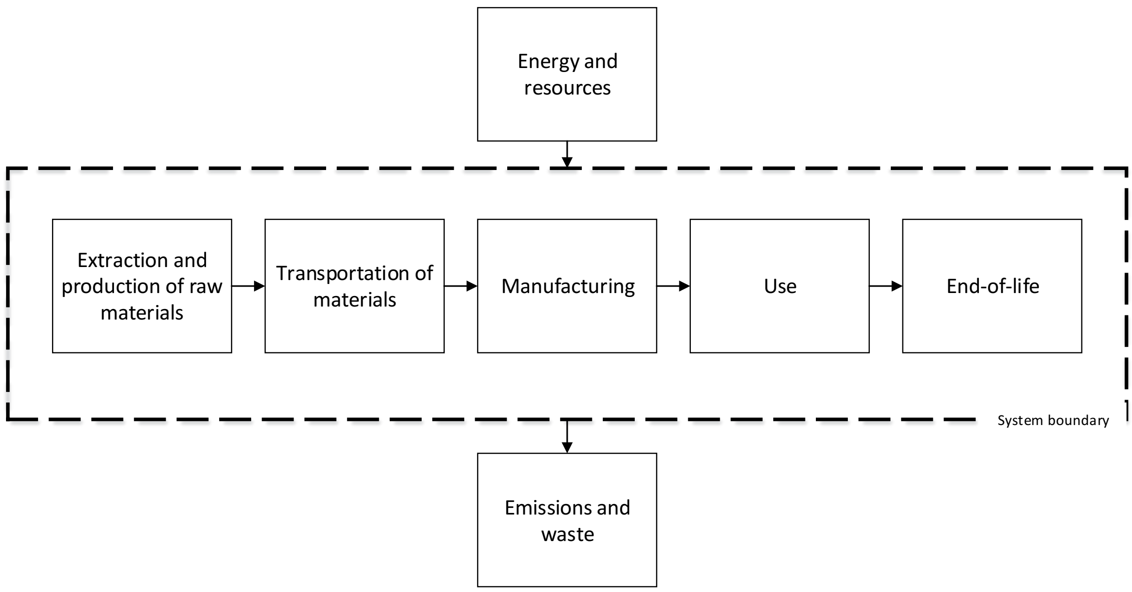


Figure 5. *A typical life cycle of a diesel engine (Modified from Li et al. 2013).*

There are several LCA studies made for vehicles operating with a diesel engine. For example, Cooney et al. (2013) compared electric public transportation buses into diesel ones with LCA. Bauer et al. (2015) conducted an LCA for passenger cars comparing diesel engine, conventional and hybrid gasoline engines, natural gas, battery and fuel cell to each other. Lee et al. (2000) conducted an LCA study for a non-road diesel tractor manufactured in South Korea. Their results concluded that the use stage was the largest contributor to environmental impact categories followed by the raw material acquisition stage. However, it should be noted that the study is almost 20 years old and since the year 2000, engines are producing less exhaust gases due to modern technology and new legislations. LCA studies have also been conducted for specific engine components. For example, Delogu et al. (2015) examined the environmental performance of different thermoplastic materials in air intake manifolds.

3.1 Structure, Operating Principle and Emission Regulations

The basic structure of a diesel engine is more or less the same, regardless of the intended use or difference in power. Basic components in a diesel engine are for example, crankshaft, connecting rod, pistons, camshaft, inlet and outlet valves, cylinder head, cylinder block, cylinder liner and flywheel (Fig 6). In a diesel engine, the fuel is ignited by auto-ignition. Auto-ignition is caused by high pressure in the combustion chamber. (Dieselengine 2016) The operating principle of a diesel engine is divided into four phases creating a cycle: intake stroke, compression stroke, power stroke and exhaust stroke. Firstly, the pistons movement downwards causes air to flow into the system from the inlet valve (intake stroke). The exhaust valve is closed at this time. In the compression stroke, the inlet valve closes, and the piston compresses the air causing the temperature to rise. Compression ratio is usually between 15:1 and 20:1. The fuel is then injected into the highly compressed air from the injector as small droplets. The fuel vaporizes, and the vapor ignites due to the high temperature in the combustion chamber. When the combustion of the vapor is complete, the combustion gases cause a pressure which forces the piston downward giving energy to the crankshaft (power stroke). Finally, the gases leave the combustion chamber through the exhaust valve (exhaust stroke). When the exhaust gases have left the cylinder, the piston is back to the upper position and the cycle is repeated. (Energy efficiency of Vehicles; Dieselengine 2016)

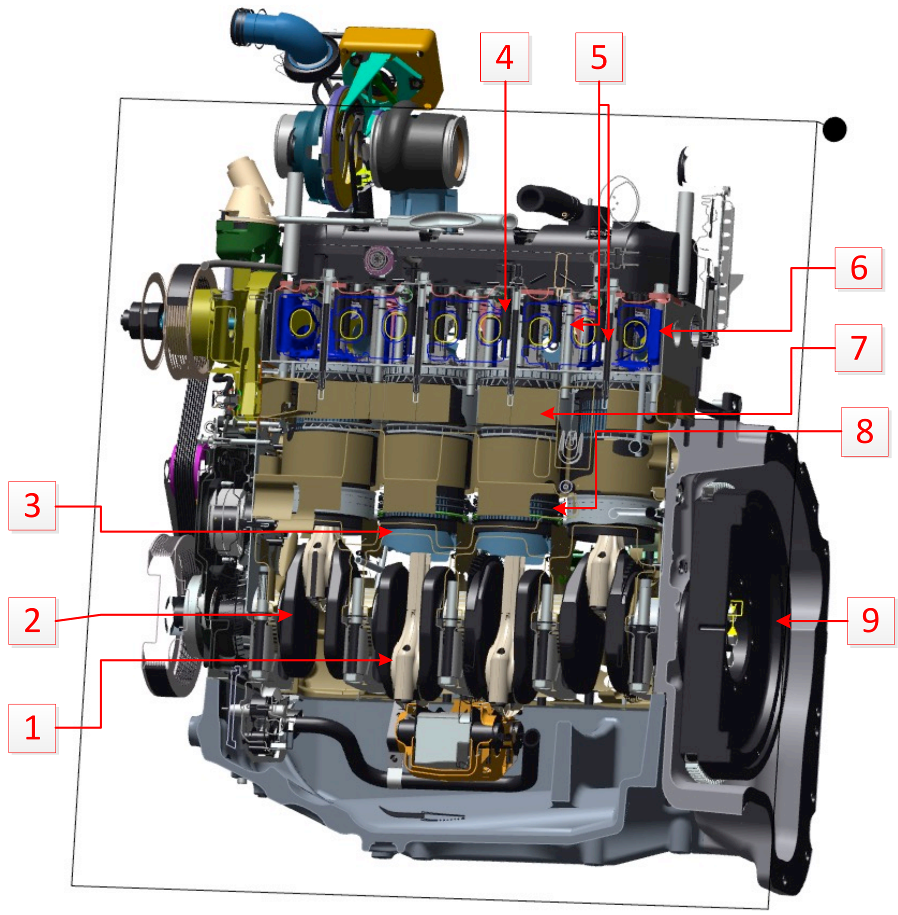


Figure 6. *Cross-section structure of a four-cylinder diesel engine with some basic components numbered (1-9) 1. Crankshaft 2. Connecting rod 3. Piston 4. Camshaft 5. Inlet and outlet valves 6. Cylinder head 7. Cylinder block 8. Cylinder liner 9. Flywheel (AGCO Power internal materials).*

Non-road engines are nowadays equipped with vast number of components that limit the emissions they produce, such as different exhaust gas treatment systems. The emission limits are set with European legislation, Directive 97/68/EC. It is the basis for the European emissions standards, Stage I-V for non-road mobile machinery. Stage I was the first standard published in 1999 and Stage IV is the current standard in force. Stage IV regulates the carbon monoxide (CO), hydrocarbon (HC), nitrogen oxide (NO_x) and particulate matter (PM) emissions of non-road engines. In 2019-2020 Stage V will set in force and it adds particle number (PN) to the list of emissions to be limited. (DieselNet) The emission control system affects not only to the amount of emissions, but also to the engines fuel-efficiency and engine efficiency. Examples for these systems are: diesel oxidation catalyst (DOC), diesel particulate filter (DPF), selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) systems. (MECA 2007)

3.2 Raw Materials

A typical diesel engine consists of steel and cast iron, aluminum and copper alloys as well as plastics and rubber parts. Steel and cast iron make up most of the mass of the engine. Non-road machines differ from road machines, such as passenger cars in a way that non-road machines need to be heavy. If the tractor was light weight, it would swing during operations and therefore lose momentum, or it would not be able to drag the plough for example. (Kivelä 2018) The following chapters present the extraction and production methods of the main materials used in a non-road diesel engine and their impacts on the environment.

3.2.1 Iron, Steel and Cast Iron

In a diesel engine, steel is used in crankshafts while cast iron is used in cylinder heads and blocks and in intake and exhaust manifolds, for example (Hoag & Dondlinger 2016). Primary steel and cast iron are made from iron ores. World's largest iron ore mining sites are located in Australia and Brazil and they are usually open pit mines (Duddu 2014). In turn, China is the largest steel producing country (World Steel Association 2017). The mined iron ores, such as magnetite and hematite, are agglomerated into more usable form by sintering. Then the sinter is reduced into pig iron, also known as hot metal, with coke or coal in a blast furnace. The pig iron is then further processed into products. The processing method depends on the desired properties. Usually, pig iron is first purified from sulphur and it is then refined and molded for further processing. The production process from iron ore to product is highly energy-, emission- and material intensive. (Remus et al 2013)

Secondary steel and cast iron are made from scrap metal by melting the scrap in an electric arc furnace. (Remus et al. 2013) Difference between steel and cast iron is in their carbon content. Steel contains less than 2.1 % of carbon while cast iron refers to iron-carbon alloys with over 2 % carbon concentration. (Meskanen & Höök 2015) Steel and cast iron are 100 % recyclable materials. It is estimated that every metric ton of used scrap steel, in the production of new steel, saves over 1400 kg of iron ore, 740 kg of coal and 120 kg of limestone. (World Steel Association 2016)

3.2.2 Aluminum and Copper

Aluminum is the most commonly used non-ferrous metal and in a diesel engine. Aluminum alloys are used for example in cylinder blocks and crankcases (Hoag & Dondlinger 2016). Primary aluminum is produced from bauxite which consists of different mineral forms of aluminum hydroxide, such as gibbsite, boehmite and diaspore among other residual minerals (Donaldson & Raahauge 2013). The world's largest bauxite mine reserves are located in Guinea, Australia and Vietnam (Statista 2017).

Life cycle of an aluminum product contains the following steps: bauxite mining, alumina production, electrolytic reduction of primary aluminum, secondary aluminum production, refining, casting, use and end-of-life processes. Most relevant emissions in aluminum production are sulphur dioxide (SO_2), carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs) and carbon dioxide (CO_2) and polyfluorinated hydrocarbons. (EEA 2016a) In addition to emissions, the refining process of bauxite into alumina, commonly known as the Bayer process, produces red mud as a by-product. Red mud is hazardous to the environment due to its high alkalinity and heavy metal content. (Donaldson & Raahauge 2013) The mining and production process consumes 7.6-11.7 GJ/t alumina. The primary aluminum production in turn, consumes approximately 46.8-61.2 GJ/t aluminum. (EEA 2016a) The life span of aluminum is long, and the metal is recyclable. Compared to the energy required for the primary aluminum production, recycling of aluminum requires only 5 % of the used energy. (IPCC 2001)

Copper is gained from copper ores, such as chalcopyrite and copper glance. (EEA 2016b) The largest mining sites are located in Chile, Peru, Mexico and Indonesia (Gupta 2013). Blister copper is produced by flash melting. The ores are oxidized in a furnace and the formed copper matte is then processed into blister copper by converting, refining and electro-refining in order to get impurities, such as sulphides and iron alloys out. Secondary copper is produced by smelting of copper scrap. (EEA 2016b) Typical emissions from copper production are: particulate matter, SO_x, NO_x, NMVOC, CH_4, CO, CO_2, persistent organic pollutants (POPs) and N_2O. Energy demand is high, especially in electrolytic processing routes. However, copper containing materials are highly recyclable. (EEA 2016b)

3.2.3 Polymers

Polymers can be naturally derived or synthesized. Synthetic polymers are manufactured with step-growth polymerization or chain-growth polymerization. The primary raw materials of synthetic polymers are called monomers and they are usually derived from the petroleum industry. (Subramanian 2017) Around 4-6 % of the world's fossil fuels goes into the manufacturing of polymers (Plastics Europe 2017). In addition to monomers, polymerization processes require one or more of the following ingredients: initiators, surfactants, catalysts, chain transfer agents, solvents, suspending agents, water-soluble polymeric compounds, inorganic compounds and inhibitors (Subramanian 2017).

The manufacturing technique depends on whether the material is thermoplastic or thermoset and what are its other physical and chemical properties. The most common processing type of thermoplastics is injection molding. Other molding process types are blow molding and compression molding. In addition, extrusion is a popular processing method. Both molding and extrusion require high temperature, making themselves energy intensive processes. Thermosets are processed chemically. (Saldivar-Guerra & Vivaldo-Lima 2013)

Emissions from manufacturing polymers and production of products depend on the manufactured polymer. However, the most significant emissions from manufacturing plastic products are VOCs, particulate matter and hazardous air pollutants (HAP). These emissions result, for example, from processing primary polymer blend, mold release compounds and byproducts of chemical reactions of heating the polymer material. (EPA 1998)

One of the most used polymers in engine components is polyamide (PA). Polyamides are used in caps, water pumps, valves and oil deflectors for example. In under-bonnet automotive parts, polyphthalamide (PPA), also known as high performance polyamide, is preferred due to its good properties in chemical and water resistance, heat aging resistance, dimensional stability, stiffness and strength at high temperatures etc. (Kemmish et al. 2011) Other polymers used in engines are acrolynitrile butadiene styrene (ABS), polyethylene (PE), polycarbonate (PC) and polyoxymethylene (POM) (Craftech industries).

3.3 Manufacturing and Assembly

Manufacturing of an engine is a form of mass production. It comprises of engineering the required components, assembling of the engine and finishing processes. Manufacturing of engine components can be divided into six types of processing methods, primary shaping processes, secondary or machining processes, forming processes, processes effecting change in properties, surface finishing processes and joining processes (Table 4). (Singh 2006) After all engine components are manufactured, they are assembled into an engine. In assembly phase, the parts are fastened together with different methods, such as gluing, welding or bolting. (Sullivan et al. 2013)

In manufacturing, the four main types of layout techniques for assembling are fixed layout, process layout, line layout, and a combination of these methods. In fixed layout, the assembled product stays put while the assemblers move around with the required tools. In line layout, the assembled product moves while the tools stay on their place. Assemblers may move with the products or stay in position beside the required tools. (Haverila et al. 2009)

Table 4. *Manufacturing of components categorized into six different processing methods and examples of manufacturing processes included in them (Singh 2006).*

Processing method	**Common manufacturing processes**
Primary shaping processes	Casting, powder metallurgy, molding of plastics, gas cutting, bending, forging
Secondary or machining processes	Turning, threading, milling, knurling, drilling, boring, shaping, grinding, gear cutting
Forming processes	Hot and cold forging, hot and cold rolling, extrusion, hot and cold drawing
Processes effecting change in properties	Annealing, hardening, tempering, normalizing
Surface finishing processes	Polishing, painting, sanding, coating
Joining processes	Welding, sintering, screwing, adhesive bonding, coupling

3.4 Transportation

Transportation is needed between all life cycle stages of an engine. Distance and the type of freight transportation are required to know, in order to assess environmental impacts of transportation. Freight transportation types can be divided into road, rail, waterborne and air transportation modes. From these, waterborne transportation by cargo ships is most preferred (80% of freight transportation in 2011). (Sims et al. 2014) Finding information on all transportation made within the product's life cycle can be difficult. For example, transportation of raw materials refers to all freight transportation made between the acquisition of raw materials and factory gate. Hereby the journey from cradle-to-gate includes such as, transportation from the mining site to the raw materials processing factory and the transport from this first factory to the next, until the desired material or product reaches the factory gate. Hence, finding verified information of the entire supply chain from cradle-to-gate for each engine component can be challenging.

When the emissions produced by freight transportation are examined, the following factors should be taken into account: infrastructure of the system, type of fuel used, energy intensity of the transportation type and activity (for example the distance of the journey). Rail freight and cargo ships produce less GHG emissions than road transportation or cargo aircraft, the latter producing highest amounts of GHG emissions. (Sims et al.

2014) When emissions to air produced by the entire life cycle of the freight transportation model were studied, it was discovered that rail freight produced the least amount of emissions to air during its life cycle, compared to road and air transportation models. In addition, road transportation produced less emission to air compared to air transportation models. (Facanha & Horvath 2006)

3.5 Use

Tractors are used mainly in lumbering and agriculture. In agriculture they are used in tilling and cultivation of soil and as front-end loader tractors. (Nylund 2016) In the use stage, impact on the environment comes from the use of diesel fuel. Diesel fuel can be divided into conventional diesel or first-, second- and third generation biodiesels (Islam et al. 2017). The type of diesel used influences the magnitude of the environmental impacts. When conventional diesel is replaced with biodiesel, environmental impacts either increase or decrease (Table 5).

Table 5. *Classification of diesel fuels and the change in environmental impacts when biodiesel is used instead of conventional diesel.*

Type of diesel fuel	Raw materials	Comparison of the environmental impacts of biodiesel and conventional diesel
Conventional diesel	Crude oil	-
1st generation biodiesel	Edible feedstocks (vegetable oil)	Impact on climate change and ozone depletion reduced by 74% and 44% respectively, when biodiesel produced from rapeseed oil was used. However, impact on acidification, eutrophication, photochemical ozone creation increased by 59%, 214% and 119%, respectively. In addition, land competition is significant in rapeseed-derived biofuels. (Gonzáles-García et al. 2012)
2nd generation biodiesel	Non-edible feedstocks (agricultural and forestry residues, waste and lignocellulosic biomass etc.)	GHG emissions reduced around 40-107% when biodiesel produced from *Jatropha* was used and 53-61%, when biodiesel made from lignocellulosic biomass was used (Kumar et al. 2008; Wong et al. 2016).
3rd generation biodiesel	Microalgae	Land use decreased by 95% and impact on climate change decreased by 21%. (Gnansounou & Raman 2016)

Even though biodiesels have considerable benefits compared to conventional diesel, there are some downsides to them as well. First generation biodiesel is made from edible feedstocks, which creates a direct competition between fuel and food. In addition, first generation, as well as some second generation, feedstocks require water and arable land, causing changes in biodiversity and creating also competition with food production. (Rulli et al. 2016) Production of algae in turn, does not require arable land and can grow in salt water and in waste water (Campbell et al. 2011; Hena et al. 2015). Hence, it does not compete directly with food production. However, microalgae-derived biofuels are still in pilot scale production. Most challenges in the commercializing of algal production lie in the harvesting and extraction phases. (Islam et al. 2017)

In addition to the choice of fuel composition, fuel-efficiency of the entire tractor can be improved and henceforth emission can be reduced. Fuel-efficiency can be enhanced by improving the fuel-efficiency of the engine, improving the fuel-efficiency of the tractor and optimizing the use of the machine. Fuel-efficiency of the engine can be enhanced by improving the engine's efficiency. Stage IV regulated engine's efficiency is approximately 44 %, at best. Different ways to improve the efficiency of an engine are lowering the engine friction, enhancing gas exchange, heat management and heat recovery. By improving these technologies, the CO_2 emissions of an engine can reduce up to 15 % (equivalent to 7% increase in engine efficiency). However, the maximum engine efficiency is reached only in optimum conditions. In reality, the engine efficiency decreases due to the technical properties of the tractor, due to the function the engine is used for and driving style. In addition, the fuel consumption depends highly on the emissions control technology. (Nylund et al. 2016)

3.6 End-of-Life

Final phase in the life cycle of an engine is a combination of different end-of-life functions. End-of-life functions include reusing of components, remanufacturing, recycling of materials and treatment of waste (Figure 7). When the engine component is reused, it is refurbished and returned to the assembly phase in engine manufacturing. If the component needs to be repaired, it is remanufactured in the component manufacturing phase. Some components and wastes are recyclable but not usable as such, hence they are returned to the materials processing phase. For example, scrap metal is melted and then processed into new products. Recycling of components is not as desirable as other alternatives, since recycling tends to preserve only the value of the raw material and materials processing techniques are usually very energy-intensive. (Liu et al. 2014)

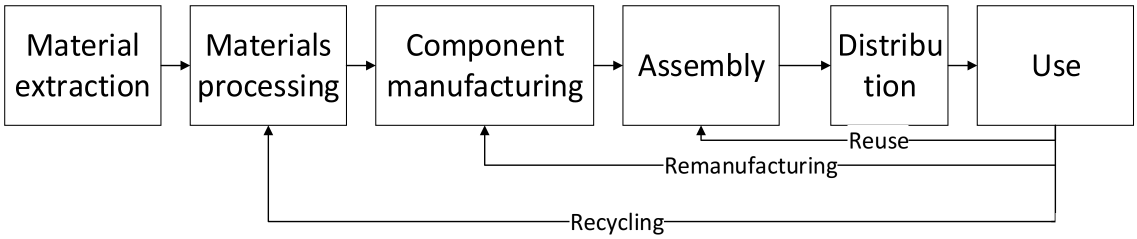


Figure 7. *Reuse, remanufacturing and recycling of engine components in material recovery value chain of an engine (Liu et al. 2014).*

Remanufacturing of components is a better option than recycling. Instead of preserving just some the raw material value, remanufacturing preserves the extracted and the refined material value, energy, water, labor and portion of the original component value. (Liu et al. 2014) When comparing energy demand of originally manufactured engine into the energy demand of the remanufactured engine, the results show that by remanufacturing components, consumed energy is substantially less (Table 6). (Sutherland et al. 2008)

Table 6. *Consumed energy in manufacturing and remanufacturing of the chosen diesel engine components. (Sutherland et al. 2008)*

Component	**Casting/Manufacturing (MJ)**	**Remanufacturing (MJ)**
Engine block (cast iron)	9970	600
Cylinder head (cast iron)	4445	1110
Crankshaft (steel)	2800	110
Six connecting rods (steel)	330	10
Six pistons (steel)	555	20
Total energy consumption	18100	1850

In addition to saved amount of energy, remanufacturing of an engine reduces the impact on ozone depletion by 97 %, eutrophication by 79%, climate change by 67%, photochemical ozone formation by 32%, acidification by 32% and on abiotic depletion by 25% (Liu et al. 2014). In comparison, Smith & Keoleian (2003) concluded in their study that remanufacturing of an engine reduced energy consumption, CO_2, CO, NO_x, SO_x and non-methane hydrocarbon emissions up to 83%, 87%, 88%, 85%, 84% and 61% respectively.

4. MATERIALS AND METHODS

The objective of the study was to quantify environmental impacts produced during the life cycle of a four-cylinder diesel engine of a tractor. The diesel engine was manufactured by AGCO Power and they were acting as the intended audience of this study. AGCO Power's engine factory is located in Linnavuori, Nokia, Finland. The conducted LCA of the engine followed the ISO 14040 and ISO 14044 standards and was done from cradle-to-grave. The calculations in the study were done using SimaPro software (v.8). Base year of the study was 2016.

4.1 Scope, Functional Unit and Allocations

The system boundary of the study included all life cycle stages of the studied engine. Life cycle stages were extraction and production of raw materials (steel, cast iron, aluminum, copper, polyamide, polycarbonate and rubber), manufacturing of the engine, distribution, use of the engine and end-of-life functions (Fig. 8). Processing of the raw materials into components and transportation of raw materials and components to the study factory were excluded due to lack of information. Manufacturing of the engine and all related infrastructure were located in Finland at the AGCO Power study factory. Product development was excluded from the manufacturing stage due to the fact that there was not any reliable information available on the product development processes for the studied engine model. The engine was placed into a tractor and distributed by Valtra. The tractor with the engine was assumed to be distributed to France and used in France. Operations done by the distributor were excluded. The functional unit (FU) in this study was chosen as "one produced four-cylinder diesel engine for a tractor".

The study factory manufactures only engines, hence all input and output flows were allocated to produced engine (FU). Allocation of emissions from waste disposal was done with the recycled content method. Thus, emissions from energy recovery processes were allocated to the producer of energy and emissions from material recovery processes were allocated to the user of the recycled content. (Johnson et al. 2013) When allocating emissions and fuel consumption of the use stage to the engine, it was assumed that most of the emissions and fuel consumption were generated in the engine (Li et al. 2013). Consequently, emissions from usage and fuel consumption were allocated to the engine in full.

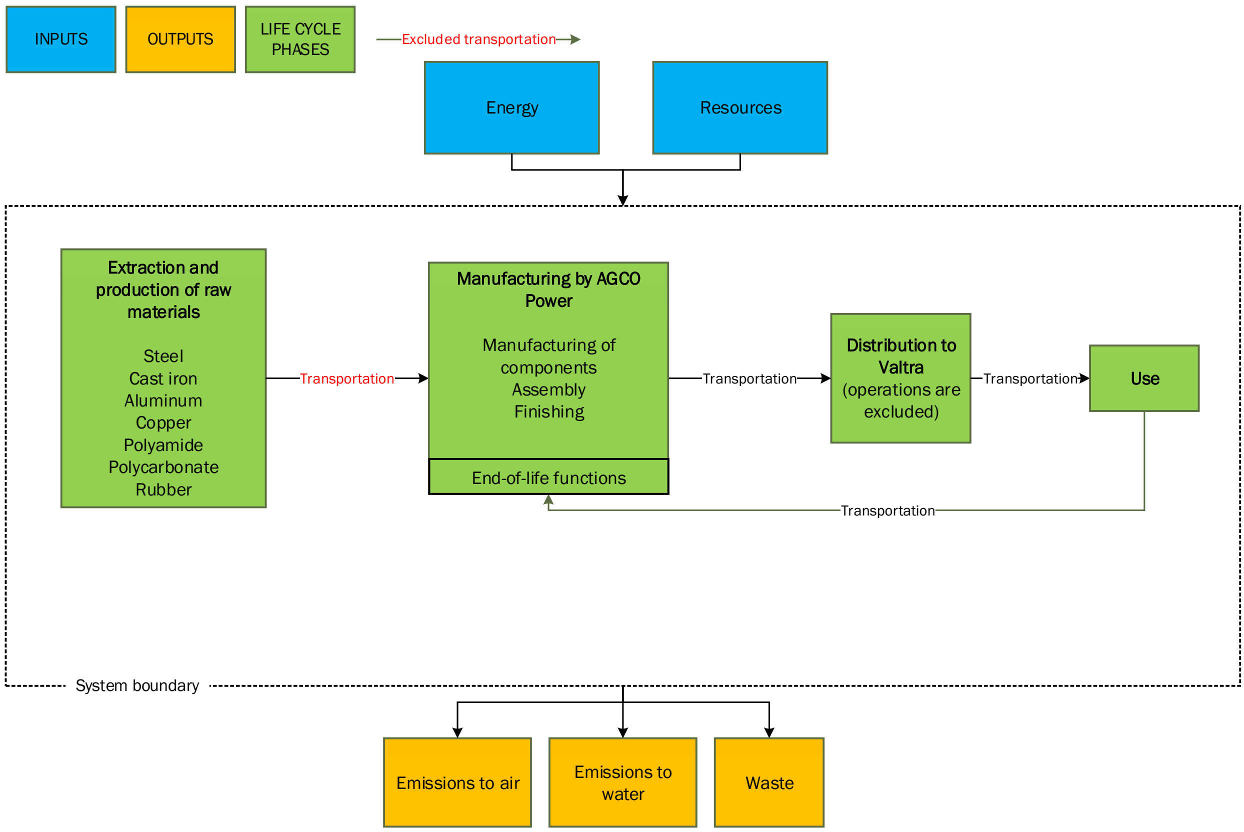


Figure 8. *Life cycle stages of the studied engine and the system boundary of the study.*

4.2 Data Sources

Input and output flows, referred as data, were collected from the manufacturer, suppliers and the distributor, literature and EcoInvent (v.3) database for each unit process in the life cycle stages (Table 7). Data was collected as primary and secondary data. Primary data was mostly activity data and it was acquired from the engine manufacturer, the distributor, suppliers and waste management companies. Direct emissions produced by the engine factory were theoretical values calculated from the activity data. Besides direct emissions from manufacturing, all emission factors for other life cycle stages were collected as secondary data from literature and EcoInvent database (v.3) using SimaPro software (v.8), hence none of the emissions were directly measured from unit processes. When emission factors from secondary sources were used, emissions were calculated with Equation 1. The base year for primary data was 2016, while the base year for secondary data varied slightly or was taken as an average of a time period.

Table 7. Used sources in data collection in different life cycle stages.

Life cycle stage	Source of data
Extraction and production of raw materials	Data managed by AGCO Power SimaPro software (v.8) • EcoInvent database (v.3)
Manufacturing	Data managed by • AGCO Power • Suppliers (energy, fuel and chemicals) • Waste treatment companies SimaPro software (v.8) • EcoInvent database (v.3) Data from literature
Distribution	Data managed by Valtra SimaPro software (v.8) • EcoInvent database (v.3)
Use	Data managed by AGCO Power SimaPro software (v.8) • EcoInvent database (v.3)
End-of-life	Data managed by AGCO Power SimaPro software (v.8) • EcoInvent database (v.3)

4.3 The Chosen Impact Method

The ILCD 2011 Midpoint+ method (v.1.10, 2016) was chosen as the impact assessment method. The method combines impact methods with their characterization factors that are considered as best available techniques for that specific impact category at the moment. ILCD 2011 Midpoint+ method was created by the European Commission Joint Research Centre. (ILCD 2011) Impact categories related to the ecosystems and resource depletion were assessed here (Table 8), hence human health related impact categories were excluded. In addition, only categories classified as level I or II (Table 1) were included in the study. Level III categories were excluded due to their unreliability. The gathered data was untrustworthy in some cases and adding an unreliable impact category would have made the results even more defective. All characterization factors used in the calculations were obtained from the SimaPro software (v.8).

Table 8. *ILCD Midpoint+ method categories assessed in the study.*

Impact category	Unit
Climate change	kg CO_2 eq
Ozone depletion	kg CFC-11 eq
Photochemical ozone formation	kg NMVOC eq
Acidification	mol H^+ eq
Terrestrial eutrophication	mol N eq
Freshwater eutrophication	kg P eq
Marine eutrophication	kg N eq
Mineral, fossil and renewable resource depletion	kg Sb eq

5. MAIN DATA AND ASSUMPTIONS

The following chapters present all input and output flows, activity data and emission factors of the life cycle stages needed for calculations. Most of emission factors were taken from the EcoInvent (v.3) database and therefore are not separately presented within the text. Emission factors retrieved from elsewhere are presented in the following chapters.

5.1 Extraction and Production of Raw Materials

The studied diesel engine contained steel, cast iron, aluminum, copper, polyamide, polycarbonate and rubber materials (Fig. 9). The total weight of the engine was 896 kg.

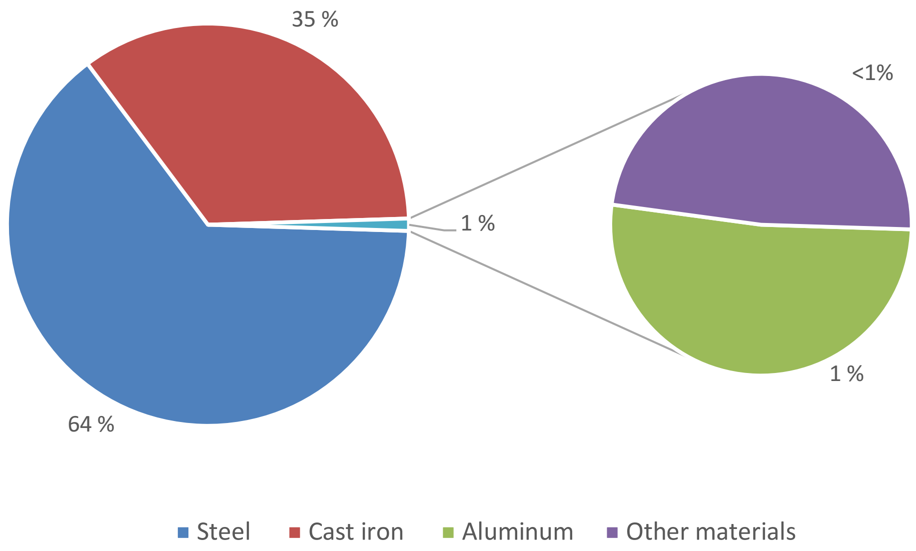


Figure 9. *Raw material composition of the diesel engine (w-%)*

Over 90 % of the mass consisted of steel and cast iron. Third largest material group was aluminum. Other materials included polyamide, copper, synthetic rubber, polycarbonate and additives. Cast iron included spheroidal graphite cast iron and grey cast iron. Aluminum materials were mostly aluminum-magnesium (Al-Mg) alloys. Copper materials were assumed to be copper based alloys. The specific types of polyamide and polycarbonate materials were unknown. Synthetic rubbers included nitrile rubber, fluorocarbon rubber and ethylene propylene diene monomer (EPDM) rubber. Additive materials were unknown, hence they were excluded from raw material stage. Emission factors for raw material extraction and production were taken from the EcoInvent (v.3) database.

5.2 Manufacturing

Manufacturing of a new diesel engine at the study factory is divided into four main phases: Manufacturing of components, automated assembly, manual assembly and finishing processes (Fig. 10). Firstly, some of the components are manufactured in the factory from ingots, such as cylinder block, cylinder head, shafts, gears and pipes while some are imported from elsewhere. After the components are manufactured, industrial robots assemble the larger, heavier parts of the engine in six production cells. Assembling starts from the cylinder block and the rest of the components are attached to the block. AGCO Power's manual assembly comprises of 39 different phases, which includes 30 workstations. In addition to employees, there are storage robots and other machinery working in manual assembly. It takes 8 hours for the studied engine to go through the manual process.

After manual assembly, finishing phase begins. In the finishing phase, the engine is washed, painted, dried, inspected by test runs, coated with rustproof and finally placed into storage (Fig. 11). The entire manufacturing process of the engine requires electricity, heat, water, chemicals and fuel. The input and output flows of the manufacturing stage of the diesel engine are examined closely in the following subchapters.

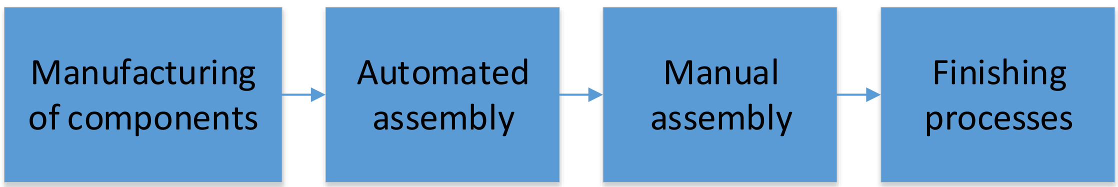


Figure 10. *Manufacturing process of the engine.*

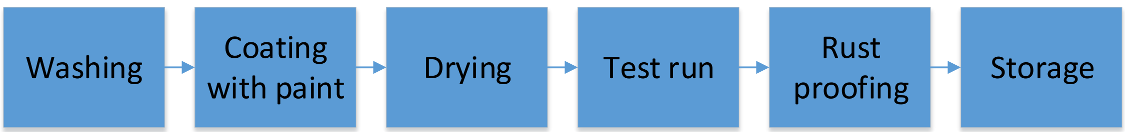


Figure 11. *Finishing process of the engine.*

5.2.1 Use of Chemicals

There were several different types of chemical used in the manufacturing processes of the studied engine at the study factory. The input values of the chemicals used for the production of one engine were obtained from the manufacturer (Table 9). The manufacturer could not measure the exact consumptions of most of the chemicals per FU. The consumption of fuel oil, methanol, propane gas and nitrogen gas were exact values for the studied engine while rest of the chemical consumptions were estimates. The consumption of chemical per FU were calculated by dividing the total chemical consumption of the study factory by the total number of produced engines in 2016.

Table 9. *Chemical consumption per one produced engine (FU).*

Class	Chemical	Amount used	Unit
Fuel oil	Diesel	2.25 [a]	l/FU
Lubricating oils	Lubricating oil	2.28[b]	l/FU
	Cutting oil	0.78[b]	l/FU
	Grinding oil	0.04[b]	l/FU
	Hydraulic oil	0.55[b]	l/FU
	Slideway lubricant	0.24[b]	l/FU
	Quenching oil	0.31[b]	l/FU
	Cutting fluid	1.62[b]	l/FU
Paint	Coating paint	0.43[b]	l/FU
Detergents for industrial use	Detergents	0.7[b]	l/FU
Chemicals for the heat treatment of metals	Methanol	0.90[a]	kg/FU
	Propane gas	0.25[a]	kg/FU
	Nitrogen gas	2.78[a]	kg/FU

[a]) An exact value for the studied engine.
[b]) An estimation calculated by dividing the factory's total chemical consumption of the chemical by the total number of produced engines in 2016.

Fuel oil (diesel) was used in the test running of the finished engine. The study factory used conventional diesel in the test runs. Most of the industrial robots and other machines required cutting fluids and other types of lubricants. Lubricant oils were also used in different machining processes, such as grinding and milling. Cutting oils, grinding oils, hydraulic oils, slideway lubricants, quenching oils and cutting fluids were classified as lubricating oils in the calculations in order to make the modelling simpler. This simplification was based on the assumption that all products under the lubricating oil-category were petroleum-based products.

The factory used gas carburizing heat treatment method in a nitrogen-methanol atmosphere for some of the gears used in the engine. Heat treatment of gears required methanol, nitrogen and propane and quenching oil. The heat treatment produced direct CO_2 and CO emissions to air (Linde Gas). However, the direct emissions of heat treatment were excluded from this study due to lack of information. Detergents were required directly in the washing of the finished engine. In addition, detergents were used for the washing of engine components and machines used in the manufacturing processes. Paint was used as a coating material of the engine.

5.2.2 Electricity, District Heating and Water Consumption

Electricity and water were directly used in the manufacturing processes of the engine. District heating was used to heat up most of the buildings located in the property. Since the factory only produces engines and their components, emissions from district heating was allocated in full for the diesel engine. Electricity, water and district heating input flows were acquired from the manufacturer (Table 10). The values were estimated by dividing the total input flow by the total number of produced engines in 2016.

Table 10. *Energy and water consumption per one produced engine (FU).*

Type of input	Consumption	Unit
Electricity	691.95	kWh/FU
District heat	433.9	kWh/FU
Drinking water	0.6	m^3/FU

In Finland, electricity from the grid comes from a production mix (Table 11). In 2016, this mix consisted of nuclear power, natural gas, coal, oil, hydropower, wind power, biomass and waste fuels. Nuclear power is the most important energy source for electricity in Finland, followed by hydropower, biomass and coal. The share of hydropower in the electricity mix varies constantly due to changes in the water supply situation. (Finnish Energy 2017) Emission factors for Finnish electricity mix were taken from EcoInvent (v.3) database.

Table 11. *Energy sources and their shares in 2016 in Finland (Finnish Energy 2017).*

Energy source	Electricity mix in Finland (%)
Nuclear power	33.7
Hydropower	23.6
Biomass	16.3
Coal	10.4
Oil	0.3
Peat	4.4
Municipal waste	1.4
Natural gas	5.3
Wind power	4.6
Total	100

District heating for the engine factory comes from a heating plant situated next to the study factory. The heating plant provides heat for both AGCO Power and Patria facilities. The heating plant operates with two boilers, one operating with sod peat the other one with wood pellets. Both boilers use light fuel oil as well, and the sod peat is mixed with wood chips in varying shares. In the calculations, it was assumed that the sod peat did not contain any wood chips due to lack of information on the amount of wood chips mixed into the sod peat in 2016.

Emission factors for the production and combustion of light fuel oil and wood pellets and the production of sod peat were retrieved from EcoInvent (v.3) database. Emission factors for peat production were averages for Nordic countries. Emission factors for light fuel oil production and wood pellet production as well as their combustion were averages calculated for European countries. The used emission factor for the combustion of peat was 103.2 t CO_2 eq/TJ (Statistics Finland 2018). In addition to GHG emissions, combustion of peat produces SO_2 and NO_x emissions. According to the sod peat supplier, calculating these emissions is impossible without knowing the concentrations of alkali sulphides and alkali earth sulphides in the sod peat, as well as some technical parameters of boilers. The shares of each energy source used in 2016 were obtained from the energy supplier (Table 12).

Table 12. *Share of fuels used in total heat production in 2016 for the study factory.*

Fuel	Share from total fuel consumption (%)
Light fuel oil	1
Sod peat	77
Wood pellets	22
Total	100

AGCO Power factory uses both drinking water and lake water in the engine production processes. Lake water is derived from Jokisenjärvi and it is used as cooling water. The lake water is circulated in a closed loop as cooling water, which means that emissions come only from the energy consumption. Energy used to derive lake water was included in the total electricity consumption of the factory. Drinking water consumption included both water used in manufacturing processes and water consumption of the employees. The study factory receives its drinking water from Nokia City facilities. Nokia City uses mostly groundwater in their water production. Emission factors were based on European averages and were taken from EcoInvent (v.3) database with the assumption that the water was treated chemically. (Nokia Water 2018)

5.2.3 Waste

The study factory produces wastewater, hazardous waste, energy waste, wood waste, mixed waste, biowaste and recyclable paper, cardboard, plastics and scrap metal. Disposal methods (excluding wastewater treatment) can be divided into incineration, composting and recycling (Fig. 12). None of the wastes go to landfills. Wastewater is dived into municipal and industrial wastewater. Municipal wastewater is treated at the wastewater treatment plant and industrial wastewater is collected as hazardous waste. First, industrial wastewater is dried at the study factory and then, the dry content is incinerated with the rest of the produced hazardous waste materials. Disposal methods and amounts of waste treated were gained from the waste management companies (Table 13).

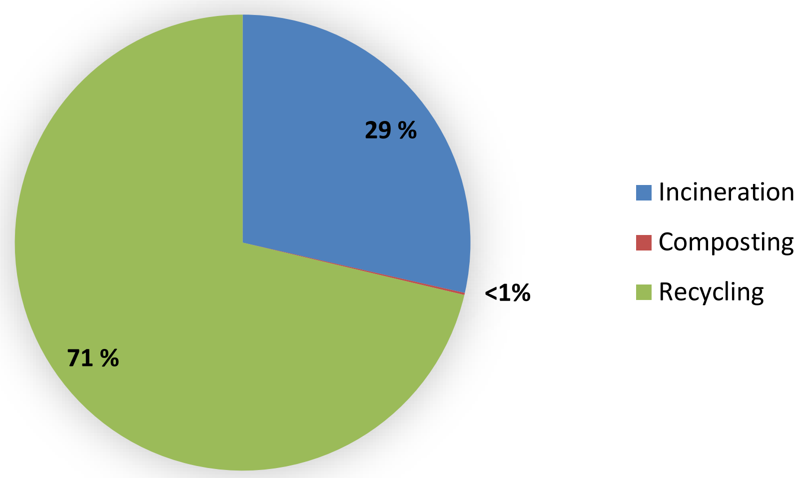


Figure 12. *Wastes from the study factory by disposal method per one produced engine (w-%).*

Table 13. *Wastes and their disposal methods per one produced engine (FU).*

Disposal method	Type of waste	Produced waste	Unit
Incineration	Hazardous waste (excluding lubricant oils)	15	kg/FU
	Mixed waste	2.67	kg/FU
	Wood waste	29.6	kg/FU
	Energy waste	5.16	kg/FU
Composting	Biowaste	0.29	kg/FU
Recycling	Cardboard	5.9	kg/FU
	Paper	0.17	kg/FU
	Recyclable plastic	0.37	kg/FU
	Scrap metal	133.4	kg/FU
	Lubricating oils (hazardous waste)	5.3	kg/FU
Wastewater treatment	Municipal wastewater	0.61	m^3/FU

Wastes were allocated to the engine according to the recycled content method (Johnson et al. 2013). Emissions from energy recovery functions were allocated to the energy producer. Hence emissions from incineration and composting were excluded here and accounted in the energy production emission factors. Emissions from recycling were allocated to the user of the recycled material. Emissions from wastewater treatment were allocated to the engine. Emissions from transportation of wastes from the study factory to the first treatment plants were included in the study. Transportation was calculated in tonne-kilometers (Table 14). All wastes were assumed to be transported using a truck with the carrying capacity of 9t (LIPASTO 2017).

In all wastes, first treatment facility refers to facilities where pretreatment of the waste occurred. Pretreatment of biowaste, hazardous waste and paper, energy and material recovery functions were done in the same location. Mixed waste, energy waste, wood waste, cardboard, plastic and scrap metal were further treated in another location. For mixed-, energy- and wood waste, the second location was the incineration facility recovering energy. For recyclable materials, the second location is the facility where the material was recovered. Because these second locations are part of energy or material recovery, the transportation was excluded between first and second treatment facilities.

Table 14. *Transportation of wastes from the study factory to their first treatment facility per one produced engine (tkm/FU).*

Waste type	**Transportation (tkm/FU)**
Mixed waste	0.104
Energy waste	0.201
Wood waste	1.155
Hazardous waste	2.892
Scrap metal	4.270
Cardboard	0.189
Paper	0.006
Plastic	0.012
Biowaste	0.014

5.3 Distribution and Use

The diesel engine was first distributed to the tractor manufacturer, where the engine was placed into the tractor. (Fig. 13). After the engine was placed into the tractor, the tractor was transported to a retailer. In some cases, the engine could be sold directly to the end-user. The tractor in this study was sold around the world to retailers and end users. Top 5 countries of sales were France, Norway, Germany, Finland and Sweden (Table 15). France was chosen as the location for use since 23% of the buyers were situated there, hence the retailer was assumed to be located in France as well. There are 122 retailers located in France, thus the distance from the tractor manufacturer to the retailer was assumed as an average distance to central France. The emissions produced by the transportation to the tractor manufacturer and transportation between the tractor manufacturer and retailer, were included in the study.

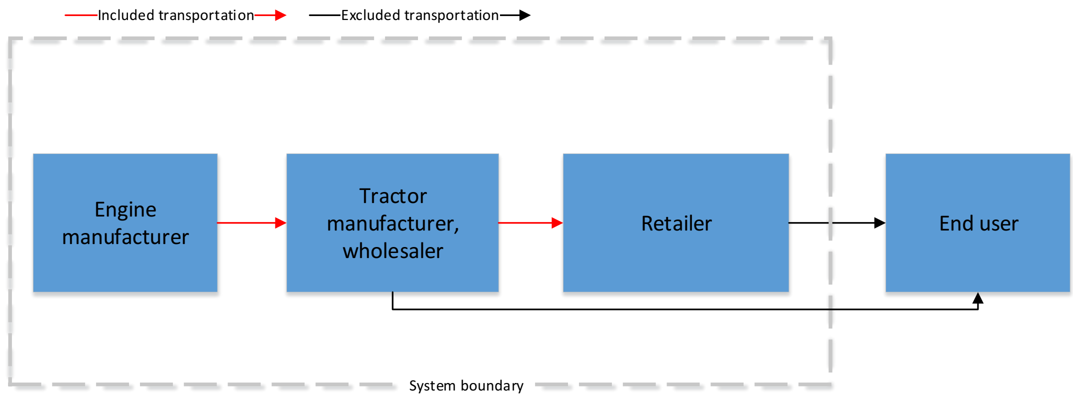


Figure 13. *System boundary of the distribution chain of the produced engine.*

Table 15. *Top 5 locations of the buyers of the produced engine.*

Country	Sold tractors (%)
France	23
Norway	14
Germany	13
Finland	9
Sweden	9
Rest of the world	32
Total	100

Transportation of the produced engine included trucks, train and a cargo ship (Table 16). Only the exact carrying capacity of the full trailer-truck was known. The type of cargo ship and truck used between Germany and France were unknown and freight transportation types that were set as default in EcoInvent database (v.3), were used. All emission factors were retrieved from EcoInvent database (v.3).

Table 16. *Freight transportation and distances within the system boundary of the distribution chain per one produced engine (tkm/FU).*

Type of freight transportation	**Transportation (tkm/FU)**
Full trailer-truck (40t) (Finland)	201.6
Train (Finland)	331.52
Cargo ship (from Finland to Germany)	896
Truck (from Germany to France)	1254.4

The lifetime of the engine in usage was assumed to be 15000 hours. It was considered to be the maximum age of a diesel engine used in agriculture, according to the manufacturer. There was not any accurate data available on the diesel engine's lifetime since it was newer production and had not reached its retirement yet. Furthermore, the lifetime of the engine depends on the intended use, frequent of use, maintenance interval, and quality of maintenance (Nylund et al. 2016). By an estimation done by the engine manufacturer, fuel consumption of the engine was assumed to be around 24 l/h.

5.4 End-of-Life Functions

Retired diesel engines are collected back to the study factory. Used engines are remanufactured (Fig. 14) and either returned back to the user or sold as remanufactured engines. The transportation from the end user back to the engine manufacturer was assumed to be the same as the distribution path (Table 16). After the engine was returned back to the factory, it was disassembled into components. Disassembly of the engine produced scrap metal and energy waste.

The life cycle of the studied engine ended in the disassembly phase. After disassembly, the life cycle of remanufactured engine begins. Most of the components can be reused in the manufacturing of a remanufactured engine while some of the components are eligible for material- or energy recovery (Table 17). In general, approximately 85 w-% of the engine is reused in the remanufactured engine and around 15 w-% of the engine's materials are recovered as material or energy. All input and output flows of end-of-life functions in the study factory were included in the data of the manufacturing stage.

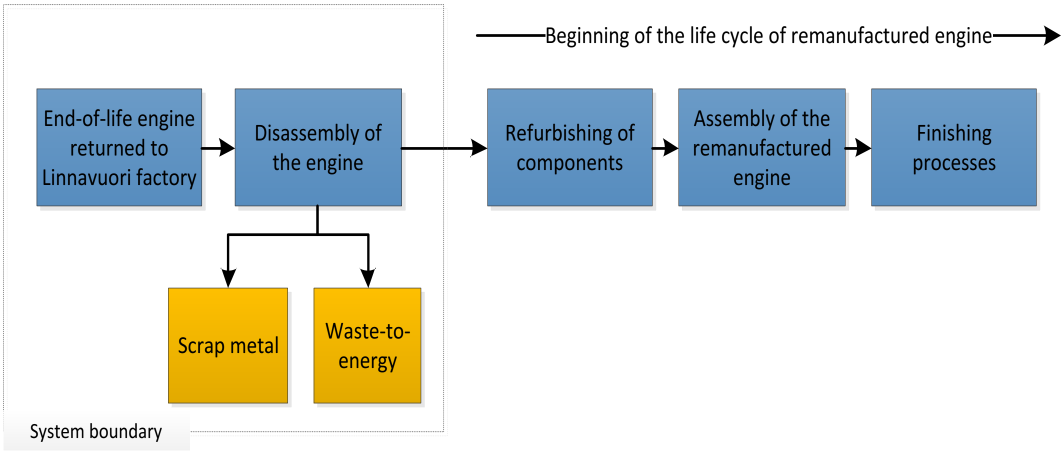


Figure 14. *System boundary of the end-of-life process. Manufacturing of a remanufactured engine.*

Table 17. *Reusable components and components suitable for material or energy recovery of the study engine.*

End-of-life function	Components
Reuse	Cylinder block, cylinder head, connecting rod, crankshaft, intake and exhaust manifolds, flywheel, gears, flywheel housing and pinion housing
Material recovery	Pistons, main bearing and cylinder liner
Energy recovery	Filters

6. ENVIRONMENTAL IMPACT RESULTS

The environmental impacts of a four-cylinder diesel engine used in a tractor were calculated with the LCA method (Table 18). The use stage produced over 94% of the emissions in each category. When the use stage was excluded from the results, raw materials stage produced most emissions (Fig. 15). Distribution and end-of-life stages had higher impacts on the environment than manufacturing stage in each category, except in climate change and freshwater eutrophication categories.

Table 18. *The total environmental impacts of the diesel engine and the shares of life cycles stages from total impacts (%).*

Impact category	Total	Unit	Shares of life cycle stages from total results (%)				
			Raw materials	Manufacturing	Distribution	Use	End-of-life
Climate change	175787.6	kg CO_2 eq	0.91	0.21	0.19	98.49	0.19
Ozone depletion	0.2	kg CFC-11 eq	0.04	0.02	0.03	99.88	0.03
Photochemical ozone formation	4633.4	kg NMVOC eq	0.14	0.01	0.04	99.77	0.04
Acidification	4689.7	mol H^+ eq	0.19	0.02	0.04	99.71	0.04
Terrestrial eutrophication	17715.5	mol N eq	0.10	0.01	0.04	99.81	0.04
Freshwater eutrophication	25.5	kg P eq	4.68	0.21	0.12	94.86	0.12
Marine eutrophication	1615.1	kg N eq	0.10	0.01	0.04	99.81	0.04
Mineral, fossil and renewable resource depletion	3.8	kg Sb eq	3.04	0.12	0.84	95.16	0.84

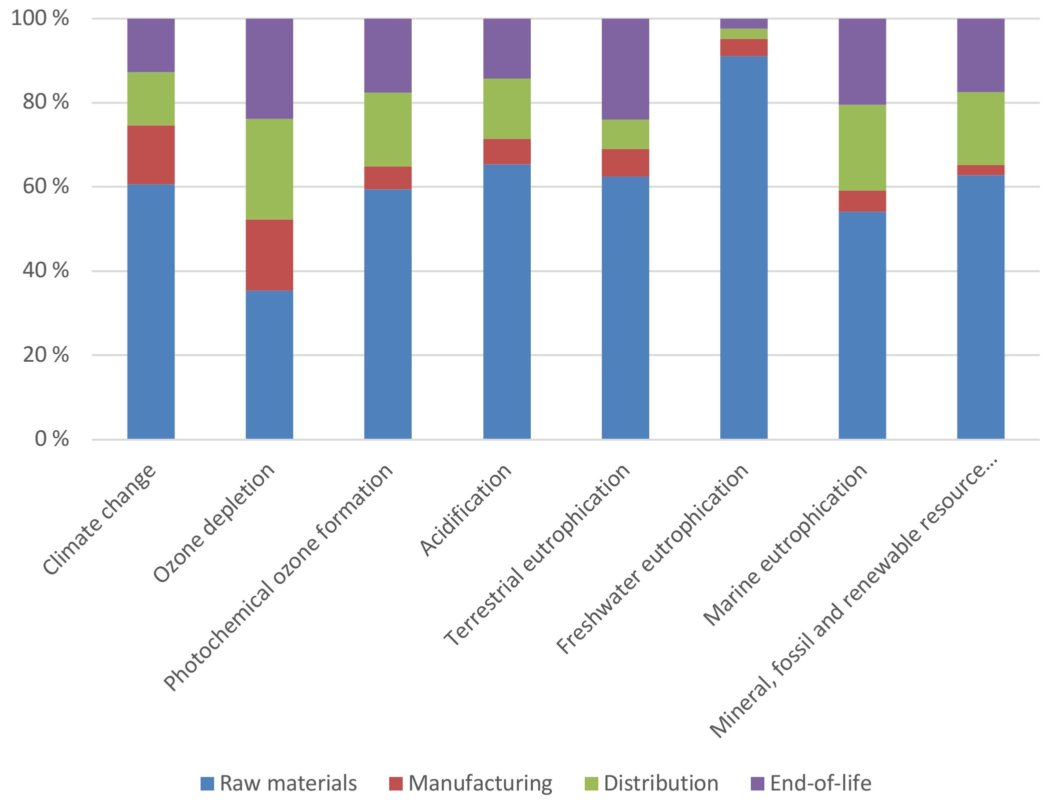
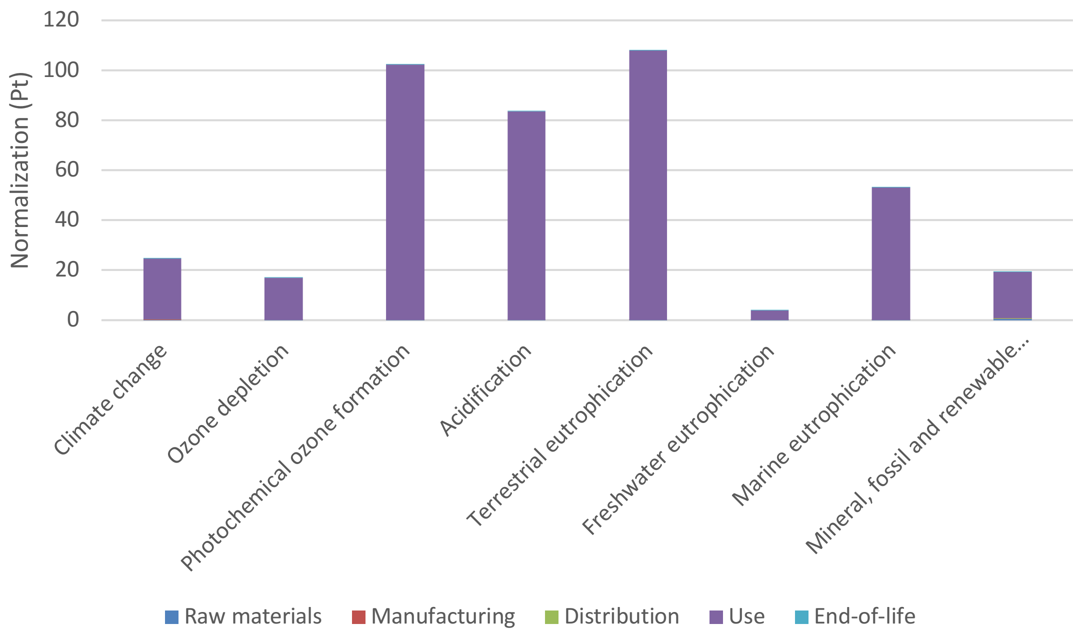


Figure 15*. The shares of environmental impacts results (%) between the life cycle stages of the engine when the use stage is excluded.*

Normalization was done with SimaPro software, which uses the EC-JRC Global, equal normalization, method when the environmental impacts have been calculated with the ILCD 2011 Midpoint+ impact assessment method. In the EC-JRC method, the results are compared into the environmental impacts produced by one average person in a year (Pt). Normalization results (Fig. 16a) show that highest contribution from the life cycle of the engine is to terrestrial eutrophication, followed by photochemical ozone formation, acidification, marine eutrophication, climate change, mineral, fossil and renewable resource depletion, ozone depletion and freshwater eutrophication. Normalization results of the environmental impacts produced by one engine during its life cycle show that the environmental impacts of the use stage are high, compared to the reference values (Fig. 16a). If the use stage is excluded from the results (Fig. 16b), the total impact on each impact category is less than one, which indicates that an average person has higher impact on the environment in a year, than the engine during its life cycle without the use stage.

(a)



(b)

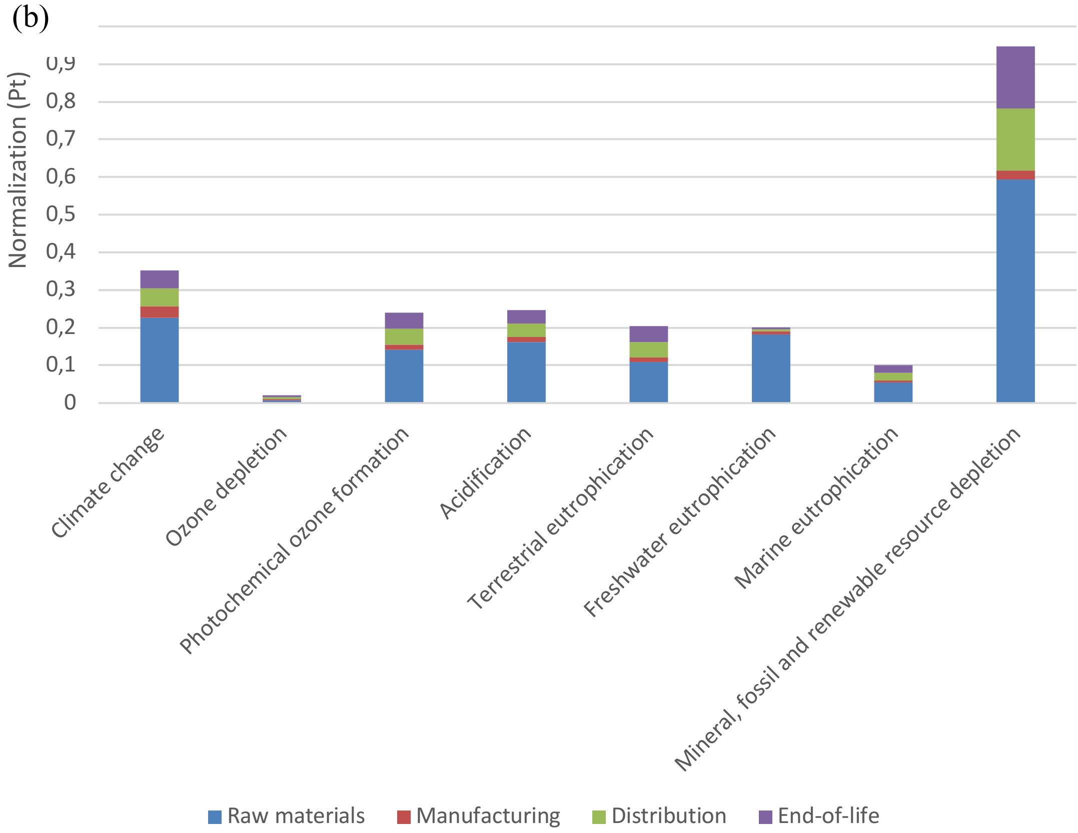


Figure 16. (a) *Total normalization results of the environmental impacts produced by the studied engine during its life cycle* ***(b)*** *Normalization results of the environmental impacts produced by the studied engine during its life cycle, when the use stage is excluded.*

6.1 Emissions from Raw Material Extraction and Production

The environmental impact results (Fig. 17) of the extraction and production of raw materials stage show that steel has the highest impact in each category. This is due to the fact that steel was the largest material group by weight in the diesel engine (64 % of the total mass). Cast iron is the second largest contributor to all impact categories except in mineral, fossil and renewable resource depletion. The production of aluminum alloys has a high impact on the mineral, fossil and renewable source category even though it only accounted 1% of the engine's weight. The high impact to the recourse depletion is due to the fact that aluminum alloy production uses zinc. Zinc is classified as scarce mineral (Henckens et al. 2016).

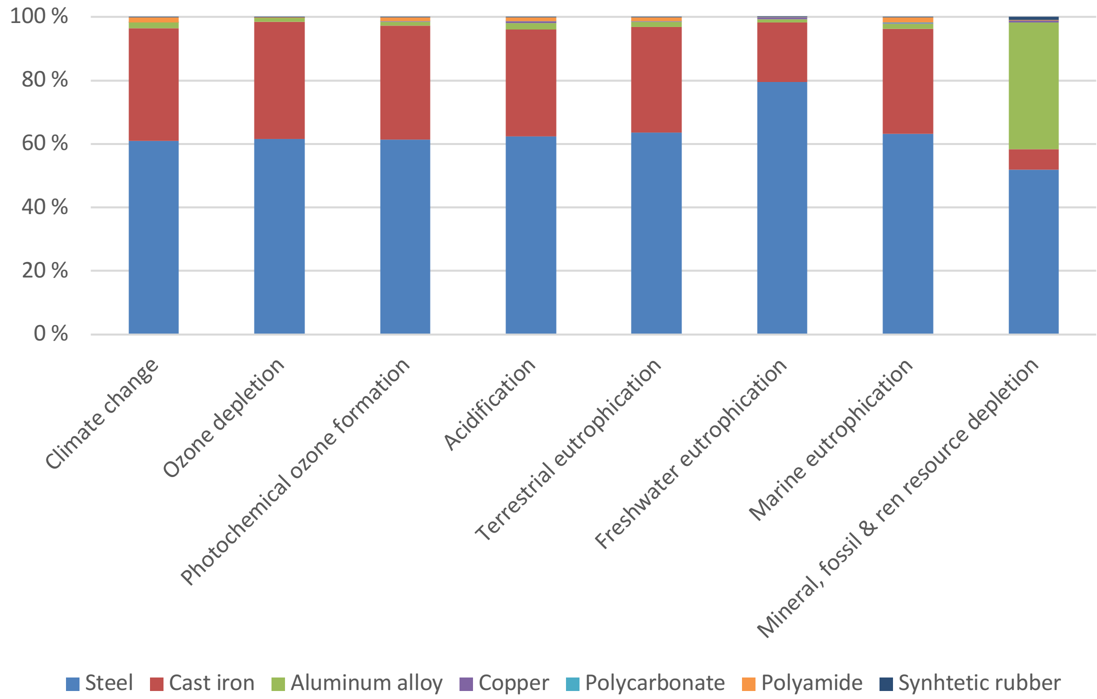


Figure 17. *The shares of the environmental impact results between raw material groups in the raw material extraction and production stage.*

The environmental impact results from raw material stage include the emissions from the extraction of raw materials and production of raw materials for further processing. The processing methods of raw materials into components were excluded from the study. It was assumed that all sub-processes were located in one facility, since there was not any accurate data available on the locations of factories related to raw material extraction and production, or on the processing methods of the raw materials into components. Type of transportation and distances from mining sites to the manufacturing facilities were also included as global averages set as default in the EcoInvent (v.3) database.

It was also assumed that best available techniques were used in materials processing (European Commission). These methods were set in the EcoInvent database (v.3) as default. In the manufacturing of steel and cast iron, it was assumed that the pig iron was produced with a converter system and scrap metal was processed in an electric arc furnace. Primary aluminum alloys and copper alloys were assumed to be processed by electrolytic processes. Secondary aluminum and copper was assumed to be processed by electrolytic refining. Polycarbonate was assumed to be manufactured by polycondenstation of phosgene and bisphenol A. Polyamide was assumed to be glass filled Nylon 6,6 synthesized from hexamethylene diamine and adipic acid. Synthetic rubber was assumed to be manufactured with the Ziegler-Natter solution polymerization of EPDM. (PRé Sustainability 2018)

The actual shares of recycled content in materials was not available from the manufacturer, hence assumptions were based on global averages reported in EcoInvent database (v.3) which included the recycling contents of materials as default. The share of scrap metal in aluminum production was assumed to be around 70%, in steel production around 50%, cast iron production around 40% and in copper production under 5%. Polycarbonate, polyamide and rubber parts were assumed to be synthesized entirely from primary materials. (PRé Sustainability 2018)

6.2 Emissions from Manufacturing

Environmental impact results from the manufacturing stage (Fig. 18) show that electricity consumption has the highest impact on all environmental impact categories except on climate change, followed by the consumption of energy in district heating, the use of chemicals and use of fuel. The activity data for calculations was collected from the engine manufacturer, suppliers and waste management companies. Direct emissions produced by the factory were calculated by the engine manufacturer. Indirect emissions were calculated by using emission factors from the EcoInvent database (v.3) and Statistics Finland (2018).

High environmental impacts from electricity consumption were due to the fact that in 2016, 33.7% of the electricity used came from nuclear power in the Finnish electricity mix (Finnish Energy 2017). Even though nuclear power is considered as a carbon neutral form of energy, the mining and enrichment processes of uranium produce heavy amounts of emissions to air and water from processes and from produced radioactive waste (Warner & Heath 2012).

Highest impact on climate change came from district heating. The impact of district heating on other environmental impact categories is lower compared to electricity category. The environmental impact results of district heating have deficiencies affecting the results. Calculations were based on the assumption that used fuel contained 77% of sod peat, 22% of wood pellets and 1% of light fuel oil, which were burned in two boilers. The emission factors contained the production of these type of fuels and the combustion of the fuels. Production of the boilers was also allocated to the fuel types in the emission factors provided by the EcoInvent database (v.3). Nevertheless, the data used for the calculations lacked information on the emissions from combustion of peat. Only the global warming potential for the combustion of peat was used since it could only be found, and the peat supplier was not able to provide any accurate emission factors. The global warming potential for peat combustion was taken from Statistics Finland database (2018). Hence, the environmental impacts of district heating might be higher in reality.

Chemicals category refers to the manufacturing of chemicals used in detergents and paint as well as methanol, nitrogen and propane used in the heat treatment of metals and different types of lubricating oils. High impact on the photochemical ozone formation category of the chemicals is due to the VOC emissions produced from painting of the engine and the production of lubricating oils. Chemical category had also high impact on the mineral, fossil and renewable resource depletion category. This was due to the manufacturing of lubricating oils. It was assumed that lubricating oils in the manufacturing were essentially manufactured from virgin materials. Though, the used lubricating oils are recycled into new lubricating oils reducing the environmental impact of the oils. In addition, the manufacturing of methanol uses zinc as a catalyst and as mentioned before, zinc is considered to be a scarce metal (Henckens et al. 2016).

The magnitude of VOC emissions from painting of the engine were retrieved from the paint manufacturer. The emissions from the manufacturing of chemicals were calculated using the data from EcoInvent database (v.3). Emissions from the use of detergents and heat treatment activities were excluded. Due to lack of information, only 63w-% of the chemicals used in detergents could be included into the calculations. The remaining 37w-% is equivalent to 190g of chemicals and the amount was considered as insignificant to the results. Diesel category refers to the low-sulfur diesel fuel used in testing of the engines. Emissions from the manufacturing of low-sulfur diesel were taken from EcoInvent database (v.3). Emission from the combustion of diesel were calculated by the engine manufacturer. Emissions examined from combustion were NO_x, CO_2, CO, PM and HC.

Waste category included the transport of wastes from the study factory to the first treatment facility. This is because of the recycled content allocation method allocates emissions from material recovery to the user of the recycled content and emissions from energy recovery to the energy producer. All wastes from the study factory were either recovered as energy or material. Hence emissions from recycling processes or energy recovery were not allocated to the study factory. In addition, emissions from energy recovery were already included in the emissions from electricity consumption.

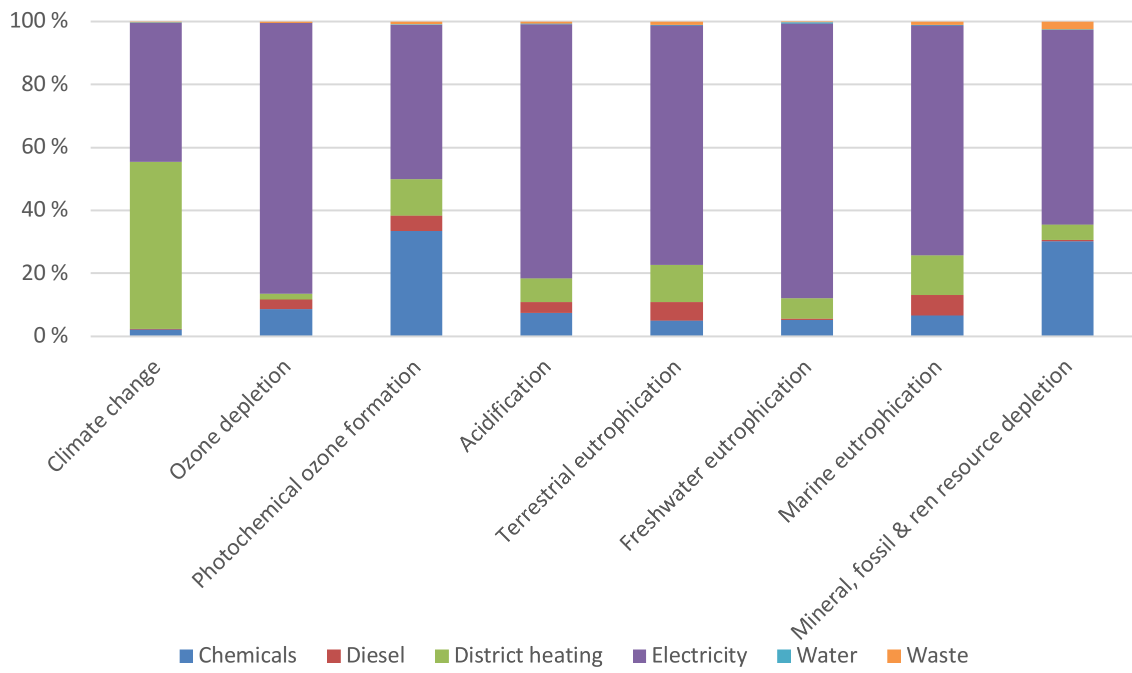


Figure 18. *The shares of the environmental impact results between input and output flows of the manufacturing stage.*

The consumption of energy, water and detergents of end-of-life functions were included in the manufacturing inventory. Waste from manufacturing included also wastes from end-of-life functions. Only emissions from the disassembly of the used engine should have been included in the inventory data, however it was not possible to separate end-of-life functions (disassembly, refurbishing, assembly and finishing processes) from the manufacturing input and output flows. Therefore, all input and output flows of end-of-life functions were included in the inventory and results.

6.3 Emissions from Use, Distribution and End-of-Life Stages

Environmental impacts of the use stage were much higher than in any other life cycle stage. This is due to the fact that during the use stage, approximately 300t of conventional diesel fuel was consumed. In the calculations, emissions from the use stage were divided into the manufacturing of the diesel and combustion of diesel categories. Emissions from manufacturing were taken from the EcoInvent database (v.3) and emissions from combustion were calculated by the engine manufacturer, as was done in the manufacturing stage. When calculating the total fuel consumption of the entire lifetime, it was assumed that the load factor of a non-road machine is 75 %. With the maximum power of 122 kWh, the average load was 91.5 kWh. Then fuel consumption of the engine was approximately 220 g/kWh. With the 15000h lifetime, the fuel consumption was 1.37 GWh (around 300t).

Emissions from distribution included emissions from transportation through the distribution chain (Fig.19). In addition, it was assumed that the engine returned via the same route back to the engine manufacturer. Hence, end-of-life stage included only emissions from the transportation from the user back to the engine manufacturer. Emissions from transportation were taken from EcoInvent database (v.3) which included the maintenance of routes, rails and the freight transportation machines.

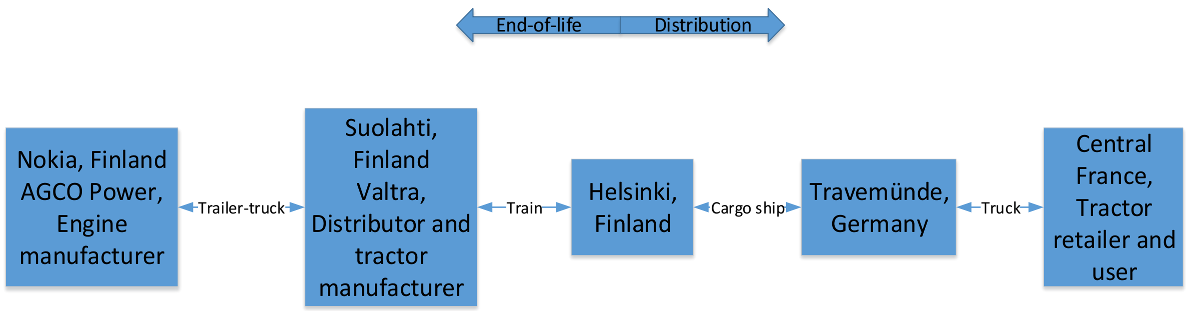


Figure 19. *Distribution chain and end-of-life route of the diesel engine.*

6.4 Uncertainty of the Environmental Impact Results

There were factors in all life cycle stages which caused uncertainty to the environmental impact results of the engine. In raw material stage, only the material composition of the engine was known. However, the recycled content of the materials was not. If the recycled content of the material changed, the results would change as well. For example, if the used steel in the engine was manufactured from 100% iron scrap instead of 100% primary steel (pig iron), environmental impacts of the raw material stage would reduce significantly (Table 19).

Table 19. *Reduction of environmental impacts (%) when scrap iron is used instead of pig iron in the manufacturing of the steel used in the produced engine.*

Impact category	Reduction of environmental impacts of the engine when iron scrap is used instead of pig iron
Climate change	96%
Ozone depletion	90%
Photochemical ozone formation	94%
Acidification	94%
Terrestrial eutrophication	89%
Freshwater eutrophication	95%
Marine eutrophication	89%
Mineral, fossil and renewable resource depletion	40%

In the raw materials stage, the locations of mining sites and production facilities caused uncertainties. Here, global average distances were assumed, which could be highly inaccurate compared to reality. In addition, the processing techniques of the raw materials were unknown and best available techniques for processing methods of raw materials were assumed to be used. Changing the processing method and distances may change the results.

In the manufacturing stage, uncertainty was caused by the estimated values of input and output flows. Energy, water, lubricating oil and detergent consumptions were calculated by dividing the entire study factory's consumption with the number of produced engines. However, the studied engine is one of the smaller engines that the factory produces. Therefore, the calculated averages might be too high since the number of produced engines contains also heavier, larger engines which require more energy, water and chemicals in their production. In addition, energy and water consumptions include also the consumption caused by the end-of-life functions, infrastructure of the factory and employees. Wastes were also allocated to the engine although wastes, such as biowaste, municipal wastewater and mixed waste, were produced mostly by employees. Hence, the emissions from wastes would be lower just for the manufacturing processes of the engine.

Data for district heating had uncertainties since the concentration of wood chips in sod peat was unknown and all emission factors for the combustion of sod peat were not available. The calculations were based on the assumption that only sod peat was used.

However, in reality, the peat mix included some wood chips too. If the calculations were done by assuming that instead of using 100% of sod peat, the mixture contains 10% of sod peat and 90% of wood chips, the results would show that the impact of district heating on climate change decreases 90%, while all other environmental impacts increase around 50%. However, these results are not completely accurate since the emissions from combustion of peat are incomplete.

The environmental impacts of the use stage, distribution and end-of-life were calculated with the assumption that only conventional diesel was used. However, in realty the diesel used could be partially renewable diesel which would change the results. Studies show that impact on climate change reduces around 53-61% and 40-107% when conventional diesel is replaced with second generation biodiesel produced from lignocellulosic biomass or *Jatropha* plant, respectively (Kumar et al. 2012; Wong et al. 2016). Transportation to the user in France had uncertainties in the distances and the type of diesel used. France has hundreds of users and 122 tractor retailers. Therefore, the transportation distance was calculated into the center of France. However, the impact of the change in the distance within France to the results was considered minor compared to the total distance of the distribution chain

7. DISCUSSION

The goal of the study was to recognize and quantify the environmental impacts produced during the life cycle of a diesel engine. In addition, the goal was to recommend procedures to the engine manufacturer regarding ways to reduce the quantified environmental impacts. Over 90% of all impacts on the environment came from the use stage, followed by the extraction and production of raw materials stage. The contribution to environmental impact categories of manufacturing, distribution and end-of-life stages together, was under 2% in each impact category. However, the engine manufacturer can mainly influence the environmental impacts produced by their own operations. Since the data from the manufacturing stage could not be targeted more specifically to each manufacturing phase and process, ways to improve the environmental performance of manufacturing can only be discussed superficially.

7.1 Opportunities to Reduce Environmental Impacts from the Manufacturing Stage

The highest impact on the environment from the manufacturing stage came from electricity consumption. If the engine manufacturer would purchase only electricity produced from renewable energy, such as solar, hydro, wind or bioenergy, some of the impacts would reduce while some would increase (Motiva 2018). The changes in environmental impacts were calculated with SimaPro software using only data from the EcoInvent database (Table 20). If the manufacturer would purchase only hydropower, all environmental impacts would reduce. The use of wind power would increase the impact on mineral, fossil and renewable resource depletion. Solar power would increase impacts on freshwater eutrophication and mineral, fossil and renewable resource depletion. Therefore, changing to hydropower would reduce all environmental impacts. Though, the electricity that comes from the grid is produced according to the electricity mix used in Finland. Hence, purchasing renewable energy would only support and prompt the production of the chosen type of energy and not directly reduce the environmental impacts of the manufacturing stage.

Table 20. *Changes in environmental impacts of the manufacturing stage (%) when the consumed electricity is produced only with 1) Hydropower 2) Wind power 3) Solar power.*

Impact category	Hydropower (%)	Wind power (%)	Solar power (%)
Climate change	43.4	39.1	29.3
Ozone depletion	85.3	83.0	73.0
Photochemical ozone formation	46.9	33.8	14.8
Acidification	78.9	54.3	28.9
Terrestrial eutrophication	73.8	61.0	42.6
Freshwater eutrophication	85.3	24.0	-7.3
Marine eutrophication	70.2	53.4	31.1
Mineral, fossil and renewable resource depletion	60.1	-28.7	-359.5

The manufacturing stage produced emissions to air from coating of the engine, heat treating of metal components and from the combustion of fuel oil. Coating of the engine with paint produces VOC emissions to air which are not filtered or treated in anyway at the study factory. The engine manufacturer could install a treatment system to reduce the amount of released VOC emissions to air. VOC emissions could be filtered biologically or treated with activated carbon or treated with thermal or catalytic oxidation, for example (Àlvarez-Hornos et al. 2011; Kamal et al. 2016; Kubonová et al. 2013). Although the amount of emissions to air produced from the gas carburizing heat treatment of components was excluded from the environmental impact results, it still produced carbon emissions to air. These emissions are not, too, filtered or treated before exiting the study factory. These emissions could be filtered or treated with different methods. For example, the carbon emission could be circulated back to the process (Arzamasov 2004).

The engine manufacturer consumes thousands of liters of diesel fuel oil yearly in the test running phase of the engines. The diesel used is conventional diesel classified as fuel oil. It would be possible for AGCO Power to use partially (15-30%) renewable diesel in the test runs, which would decrease most of the environmental impacts. The use of renewable diesel however, has some downsides, such as competition on arable land with food production, which need to be kept in mind (Gonzáles-García et al. 2012; Kumar et al. 2008; Pubule et al. 2011; Wong et al. 2016). If the engine manufacturer switched from fuel oil to partially renewable diesel, they would have to pay taxes for it, unlike with fuel oil. Hence, the cost of switching from fuel oil to renewable diesel would be high. In addition, 100% renewable diesel would not be eligible for test runs, since it slightly reduces the efficiency of the engine, which causes problems with the customers. Though, the engine manufacturer has set a goal that by the end of 2030, part of the diesel used will be renewable.

Water and chemical consumption could be reduced by improving the maintenance operations and optimizing processes of different machines used in the engine manufacturing. If the consumption of water and chemicals decreased by 20%, the environmental impacts would decrease too (Table 21). Although, reducing chemical and water consumption would not cause drastic reductions in the environmental impacts of the manufacturing stage. However, the reduction in mineral, fossil and renewable resource depletion would be 21% which can be considered high. Since there is not any real data available on the consumption of water and chemicals of the machines, these reduction calculations have a lot of uncertainties which need to be remembered.

Table 21. *Reduction in environmental impacts of the manufacturing stage (%) when water and chemical consumption is reduced by 20%.*

Impact category	**Reduction when water and chemicals are used 20% less**
Climate change	1.8
Ozone depletion	2.0
Photochemical ozone formation	8.6
Acidification	3.6
Terrestrial eutrophication	2.4
Freshwater eutrophication	5.9
Marine eutrophication	3.0
Mineral, fossil and renewable resource depletion	21.3

7.2 Comparison of Environmental Impact Results into Reference Studies

The order of magnitude of the environmental impact results of different life cycle stages from this study are consistent with other LCA studies regarding a diesel engine. The order of highest impacts produced by a life cycle stage is similar in each study. The use stage has highest impact on the environment and second highest impacts come from raw material acquisition. The magnitudes of the environmental impacts vary, however that is typical since the engines in the studies are manufactured for different purposes and the scopes and methodologies used, are different in each study. (Jian et al. 2014; Lee et al. 2000; Li et al. 2013)

The environmental impact results of climate change were compared to a reference study climate change results (Table 22) (Li et al. (2013). The reference study examined a six-cylinder diesel engine used in a bus. The weight of the engine was 860 kg. In comparison, the weight of the four-cylinder engine is this study was 896 kg. Climate change was chosen as a reference impact category since it was examined in both studies and the characterization factors used were similar, making the results more comparable. Raw material, manufacturing and use stages were examined since they were included here and in the reference study. The comparison shows that the magnitude of the impact on climate change from this study are less than in Li et al. (2013) reference study. The results from the reference study for climate change are 63% higher, which could be due to some differences in scope and used primary and secondary data. However, the shares of different life cycle stages are of similar magnitude in raw materials and use stages. The share of manufacturing varies, here it was 0.21% and in the reference study, manufacturing produced 0.88% of the climate change impact. The variance in the environmental impact results of the manufacturing stages between this and the reference study is due to differences in the manufacturing processes, in the geographical location and in the scope of components included in the studies.

Table 22. *Comparing the impact on climate change from here to a reference study (Li et al. 2013).*

	Total impact on climate change (kg CO_2 eq)	**Raw materials**	**Manufacturing**	**Use**
Own diesel engine	175789	0.91%	0.21%	98.5%
Diesel engine manufactured to be used in a bus	474000	0.89%	0.88%	97.7%

7.3 Strengths and Weaknesses of This Study

In this study, the use of LCA method provided the framework on finding out the environmental hotspots in the life cycle of the diesel engine. More importantly, the process of finding data for the calculations raised many defects in the manufacturing stage, which turned out to be an asset of this study. The defects from manufacturing stage provided a comprehensive list of suggestions on operations that the company could do, in order to reduce environmental impacts of the manufacturing process. The most pressing issue was the lack of data on each manufacturing process and machine. In the future, the engine manufacturer should measure more accurately the consumption of energy, water and material used per process or machine at the study factory.

Uncertainties in the environmental impact results were mostly associated with the collected data. The lack and quality of data (activity data and emission factors) was considered to be the main weakness of this LCA. Assessing the reliability of the data is a crucial part of the LCA method. When the used data is not exact, the results cannot be interpreted literally and thus, can only be used more as a guideline. In this study, most of the result relied on the default data provided by EcoInvent database (v.3) or were estimates made by the engine manufacturer. Hence, the recommended operations on reducing the environmental impacts of the manufacturing stage were superficial.

In this study, the economic and social perspectives were not taken into account. If the economic perspective was applied in to the manufacturing stage, it would be noted that most of the recommended operations are quite costly and do not offer any direct economic benefits, only environmental. For example, changing from fuel oil to partially renewable diesel in the test running phase would reduce environmental impacts, but also increase costs. A comprehensive LCA would consider all aspects in order to find out the alternative which serves the economic, environmental and social aspects equally.

8. CONCLUSIONS

The environmental impacts produced during the life cycle of a non-road diesel engine were assessed with the LCA method. Normalization results showed that highest burden from the life cycle of a diesel engine was on terrestrial eutrophication, followed by photochemical ozone formation, acidification, marine eutrophication, climate change, mineral, fossil and renewable resource depletion, ozone depletion and freshwater eutrophication. The order of magnitude of the produced impacts on the environment by the life cycle stages was the use stage, raw material extraction and production stage, distribution stage, end-of-life stage and manufacturing stage.

From the environmental impact results, the use stage had the highest impact on the environment in each impact category. The high impact on the environment from the use stage was due to the combustion of fuel. The lifetime of the engine was estimated to be 15000h and during that time, the fuel consumption was estimated to be 1.37 GWh in total. The calculations based on the assumption that only conventional diesel was used in the usage of the engine. The environmental impacts could decrease if conventional diesel was replaced with renewable diesel.

Raw material stage had the highest impact on the environment after use stage. High impact on the environment from raw material stage was due to energy intensive processing methods used in steel and cast iron production. Over 90 w-% of the engine comprised of steel and cast iron. When the engine is manufactured for a tractor, the steel parts cannot be replaced with lighter materials, such aluminum because the tractor needs to be heavy in order to perform. In the raw material stage, only the extraction and production of raw materials were assessed. In other words, the production of components from the raw materials was excluded.

Manufacturing stage contributed least to the environment from all life cycle stages. Impacts to the environment from the manufacturing stage came mostly from the consumption of energy. If the manufacturing company purchased renewable energy and switched from conventional diesel to partially renewable diesel in test runs, they would enhance their environmental performance. The use and manufacturing of chemicals produced highest impacts on the environment after energy use in the manufacturing stage. By installing suitable treatment systems to painting and gas carburizing heat treatment processes, the emissions produced from these processes would not be released to the air and thus, the impact on the environment would decrease.

In the future, the engine manufacturer should measure energy, water and chemical consumption of each machine and production phase. In addition, they should separate the produced wastes into waste produced by employees and waste produced from the engine manufacturing. When these input and output flows are updated, they should bring this LCA study up-to-date. In the future, LCA should be implemented as part of the research and development phase of the engine. The manufacturer should also consider purchasing their raw materials closer to the factory and hence reduce emissions from transportation. LCA study should be conducted to another type of diesel engine in order to see if the results differ significantly.

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