CHALMERS
UNIVERSITY OF TECHNOLOGY

Life Cycle Assessment of Alternative Business Models for Volvo Trucks

Master of Science Thesis in the Master Programme, Industrial Ecology

Zhengrong Chen
Zheng Lu

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2017

REPORT NO: 2017:1

Life Cycle Assessment of Alternative Business Models for Volvo Trucks

Zhengrong Chen
Zheng Lu

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2017

Life Cycle Assessment of Alternative Business Models for Volvo Trucks
Master of Science Thesis in the Master Programme, Industrial Ecology

ZHENGRONG CHEN
ZHENG LU

Technical report no: 2017:1
Environmental Systems Analysis
Department of Energy and Environment
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone +46(0)31-772 1000

Cover: Volvo FH Series Truck

Printed by Chalmers Reproservice
Göteborg, Sweden 2017

Life Cycle Assessment of Alternative Business Models for Volvo Trucks
ZHENGRONG CHEN
ZHENG LU
Department of Energy and Environment
Chalmers University of Technology

Abstract

Product-service systems (PSS), as a sustainable business model， is of increasing interest for Volvo Trucks. This study, as part of Mistra REES project, explores whether PSS is an environmentally advantageous business model or not, compared with traditional sales, that is prevailing in the current business. A life cycle assessment (LCA) is applied to assess PSSs' environmental potential, from a fleet perspective.

A focus of this study is placed on the two most likely changes connected to the move towards PSS, namely maintenance and remanufacturing. Three scenarios (traditional sales, PSS with a focus on the change of maintenance services and PSS with changes in both maintenance and remanufacturing of engines) are set up to assess the environmental performance of the two business models. Four environmental impact categories for characterization (global warming potential, acidification potential, abiotic resource depletion potential and human toxicity potential) and one weighting method, EPS, are chosen for the impact assessment.

The results show that, without considering fuel consumption, maintenance may result in an improvement of the environmental impacts by nearly 55% compared with traditional sales, and engine remanufacturing would contribute to a further improvement by 1.5%. It is notable that maintenance would have a large contribution to the lower environmental impacts of PSS, if the designed truck lifetime could be realized through better maintenance provision for trucks from a long-term sustainability perspective, the PSS model combining with maintenance and/or remanufacturing would thus highly probably be more environmentally benign than traditional sales. However, from a short-term sustainability perspective, it remains uncertain as to whether PSS is more environmentally advantageous than traditional sales since fuel consumption is still a non-negligible problem facing the truck industry nowadays when fuel technology improvement is considered. Notably, if fuel efficiency improvements are considered, engine remanufacturing may lead the PSS business to a worse environmental performance due to the delayed introduction of more fuel-efficient technologies.

Keywords: Volvo Trucks, LCA, traditional sales, PSS, maintenance, remanufacturing.

Acknowledgements

We would like to express our gratitude to Volvo Group Trucks Technology and the department of Energy and Environment at Chalmers University of Technology for commissioning this study. We would like to thank our three supervisors, Lisbeth Dahllöf from IVL Svenska Miljöinstitutet, working for Volvo Group, and Anne-Marie Tillman and Daniel Böckin from Chalmers as they are especially of great help to us in guiding this study. Thanks would be expressed to Derek Diener and employees of Volvo Trucks and Group Trucks Technology whom we had interviews with for their assistance in data collection.

Table of contents

List of Abbreviations

ADP	Abiotic resource Depletion Potential (RDP)
AP	Acidification Potential
BOM	Bill of material
CTUh	Comparative Toxic Unit for humans
DPF	diesel particulate filters
EAA	European Aluminum Association
ELU	Environmental Load Units
EOL	End-of-life
EPS	Environmental Priority Strategies
FU	Functional unit
HTP	Human Toxicity Potential
IISI	World Steel Association
ISSF	International Stainless Steel Forum
LCA	Life cycle assessment
LT	Lifetime
Maint.	Maintenance
ODP	ozone depletion
PSS	product-service system
Reman.	Remanufacturing
TS	Traditonal sale
UT	Uptime

List of Tables

List of Figures

1. Introduction

Human civilization has flourished, and the economy has gone through exponential growth since the Industrial Revolution. Technology progress drives the development of scale economy and productivity that enables plenty of goods to be supplied to consumers through mass production (Allen, 2006). With the shift of economic structure, human life and lifestyle have undergone a significant change. Human development concerning the improvement of living standard, the extension of life longevity and the rise of political freedom, etc. has been documented on a global scale. It is evident that we humans are thriving in an era of unprecedented prosperity.

Such prosperity, however, is created on the basis of our reliance on the ecosystem and nature. For sustaining the prosperity, we humans have been overexploiting the earth over the past two centuries. As is known, the human ecological footprint altogether is far beyond the carrying capacity of the earth system (D'Elsa, 2010). The human activities have altered the earth system and the environment that we humans live in have deteriorated. The crisis resulting from effects of the activities, e.g. climate change, resource scarcity and so on have emerged.

It becomes more and more evident that to maintain the continuous prosperity is difficult in the face of these crises, which is subject to various constraints from nature and the environment, e.g. limited availability of resources, limited assimilative capacity. To address these challenges, various measures for dematerialization have been proposed in the academic community as a solution that aims to reduce the input of raw materials and waste generation. One of the measures is the adoption of a new business model - Product-service system (PSS). It is perceived to be an approach to sustainable industrial practice as it could, in theory, contribute to a decline in demand for raw materials by offering dematerialized services and facilitate innovation through increased interaction between producers and customers (Tukker, 2015).

It is capturing the attention of an increased number of manufacturing companies who have a high reliance on natural resources. They see the implementation of PSS business as an opportunity to gain a competitive advantage in the manufacturing industry. On the one hand, there can be economic improvements, and on the other hand, the corporate environmental performance has the potential to improve under the new model.

Volvo Trucks, one of the largest truck manufacturers in the world, is looking into alternative business models such as PSS. Under the traditional sales model, vehicles are sold to customers after manufacturing and subsequently traded from one customer to another until they are finally discarded. Volvo's responsibility for the trucks ends after the transaction with the customers. The services provided by Volvo Trucks are not bound with the sales of trucks, but are rather optional for customers to purchase. Different from traditional sales, trucks in PSS business are not sold to customers but are instead leased to clients. In other words, Volvo Trucks retains the ownership of the truck and only provides customers with the function of transportation capability. Volvo Trucks is in this case responsible for the operation and maintenance of trucks, take-back and end of life treatment during their full lifetime. This is different from the leasing business that Volvo Trucks is currently operating, where trucks usually end up being sold on the market after a few years of leasing. Volvo Trucks is only responsible for trucks during the leasing period and not the entire lifespan of the trucks.

1.1 Research aim

The purpose of this study is to understand the potential environmental effects which result from the shift of a business model from the existing business to PSS at Volvo Trucks. This is done by conducting a Life Cycle Assessment (LCA) on an alternative PSS business model for Volvo Trucks, under which transport is sold to customers through truck leasing and comparing this with Volvo Trucks' existing model centering on truck sales.

2. Background

2.1 Literature review- PSS and its environmental potentials

A literature review was performed to comprehend the environmental potentials of a PSS -based business. The review drew on a databases Scopus in searching for papers which shed light on an environmental dimension of PSS. It generated several dozens of articles by searching the keywords functional sales and PSS, in various combinations with automotive industry, sustainability, environmental improvements and environmental performance, etc. However, not all of them were relevant for the review. Through subsequent abstract and manual content checks, 16 papers were finally selected for further study.

PSS is an emerging concept, which refers to a new business model rising to attention that aims at meeting customers' needs and creating added values for customers through servitization. It is defined by Tukker and Tischner (2006 cited in Tukker, 2015) as "a mix of tangible products and intangible services designed and combined so that they are jointly capable of fulfilling final customer needs". Geum and Park (2011) describe it as a bundle of products and services to deliver functions for customers. For example, it is interchangeably applied with other terms in the academic community. As Sundin and Bras (2005), Beuren et al., (2013), Lindahl et al. (2014), and Barquet (2016) depict, it is sometimes called functional sales, functional economy, service economy, integrated product service offering and so on. Nevertheless, these terms are not exactly equated with PSS. As is pointed out by Williams (2007), functional sales are a part of PSS. It can be substituted by PSS only in the case of sales of functions and utility through e.g. leasing, sharing and pooling etc. It is noted that PSS refers only to functional sales whenever it is used in this study.

As is shown by the definition, PSS does not necessarily deal with circular business as it puts an emphasis on the integration of products and services. However, it is often employed to approach the shift of business toward a circular economy via engineering activities, such as remanufacturing, reusing and recycling (Lindkvist and Sundin, 2016). Many sustainability researchers have taken it as a solution to unsustainable consumption in the manufacturing sector towards a more resource-efficient and circular industrial practice. Ideas built on PSS by sustainability researchers e.g. (Maxwell et al., 2006; Geum and Park, 2011; Gaiardelli et al., 2014; Mahut et al., 2015; Vezzoli et al., 2015) are proposed to optimize the economic performance of PSS for companies and to attain environmental and social improvements, while functionalities that customers want are provided. PSS is regarded as a promising way to approach more efficient resource consumption for the sake of the environment based on a shift of focus from selling products to meeting customers' needs (Chierici and Copani, 2016).

Companies have the potential to gain environmental improvement and economic profit as well as corporate competitiveness at the same time by implementing PSS properly (Beuren et al., 2013).

PSS, as indicated by Williams (2007), Tukker (2015), Vezzoli et al. (2015), Chierici and Copani (2016) and Pigosso and McAloone (2015) provides manufacturing companies with an opportunity to reorient their business towards sustainable production and consumption through the provision of dematerialized services. This can be comprehended from the business standpoint of producers that corporate profits are no longer directly correlated with sales of products as they have been in a conventional product sales business, but with the relevant functions on offer (Tukker, 2015). Under functional sales, products that serve as carriers to deliver a function are now, from an economic perspective, a cost for the producers instead of a profit (Pigosso and McAloone, 2015). The producers, therefore, have an incentive to reduce the lifecycle costs of a product in consumption of energy, materials, and resources to attain higher revenues (Williams, 2007; Tukker, 2015; Vezzoli et al., 2015; Chierici and Copani, 2016; Pigosso and McAloone, 2015).

In a PSS business model, there is an extension of producer responsibility and/or a change in ownership structure, meaning that the responsibility for the management of products lies with the producer (Chierici and Copani, 2016). Opportunities for dematerialization and cost reduction lie in a variety of engineering activities over the lifecycle of products. Proposed activities for dematerialization focus entirely on stages of product development, use and end-of-life management, including designing, maintaining, remanufacturing, reusing, recycling and assisting services for customers in usage of products (Beuren et al., 2013; Gaiardelli et al., 2014; Lindkvist and Sundin, 2016; Mahut et al., 2015; Sousa and Cauchick Miguel, 2015; Vezzoli et al., 2015; Chierici and Copani, 2016). Among them, designs for durability and maintenance aim to prolong products' lifetime, while the others i.e. design for remanufacturing and maintenance, remanufacturing, reusing, recycling and assisting services are directly introduced to improve resource use efficiency (ibid.). All of them are in theory able to contribute to potential environmental improvements one way or another (ibid). A study performed by Lindahl et al. (2014) has confirmed the potential of PSS for environmental improvement through the adoption of some engineering activities. A transition to PSS combined with engineering activities is supposed to have both economic and environmental advantages for manufacturing companies.

However, Maxwell et al. (2006) argue that PSS is not intrinsically an environmentally advantageous business model as it is contextualized dependent and it needs to be examined in the combination with the context. Concerns over PSS failure that use these activities have been raised by Sundin and Bras

(2005), Tukker (2015) and Chierici and Copani (2016). For example, to prolong the lifespan of products through design for durability is often associated with adverse environmental impacts in the case that technological progress is fast, considering the long-life use of less efficient technologies (ibid.). The other example is that a durable design serves no use for the environmental advantages of PSS as consumers questing for fashions and aesthetics are likely to withdraw from the obsolete products earlier (ibid.). Application of engineering activities for dematerialization is not necessarily to be able to fulfill its original design purpose for environmental improvements.

To address the failure of PSS conceived both economically desired and environmentally benign, a concept, remanufacturing with upgrade based on engineering activities, has been put forward. It allows products to be updated to State-of-the-art technologies and functions and extend their value life (Sundin and Bras, 2005; Chierici and Copani, 2016). A PSS based on this concept is thought able to fix the failure of durable design contested by Sundin and Bras (2005) and Chierici and Copani (2016). They claim that it has large potentials in dealing with environmental problems resulted from consumption of products.

Some researchers disagree as to whether engineering activities can overcome the failure of PSSs' design or not. Beuren et al. (2013) and Sousa and Cauchick Miguel (2015) argue for the importance of cultural factors to the success of a PSS. They stress that the planned environmental improvements cannot be achieved if consumers do not accept the PSS. The environmental potentials of PSS must, therefore, be considered and assessed in combination with specific culture and customers' attitudes toward PSS and products. Tukker (2015) and Vezzoli et al. (2015) illustrates the deficiency of claims made by Sundin and Bras (2005) that rebound effects are ignored in PSS. Pigosso and Vezzoli et al. (2015) argue that a PSS not necessarily contribute to environmental advantages even though the PSS is well-designed. They point out that the conceived potential of environmental improvements of PSS is often offset or even reversed by rebound effects resulted from changes in consumption patterns. Vezzoli et al. (2015) further argue, environmental impacts of increased transportation caused by system change might be a factor that decreases the environmental improvements of a PSS. All these concerns add uncertainties to the environmental potentials designed for a PSS business. Despite the difference of the contentions, Sundin and Bras (2005) admits that in practice, the implementation of PSS does not fulfill the expectation of sustainability researchers.

Despite the disparate views, PSS designed by a complex interrelated system of society is not inherently a resource-efficient business model considering cultural factors and effects of system change. A PSS-based business is not by definition more environmentally sound than a traditional product sales business. The environmental performance of a PSS-based business needs to be assessed on a case by case basis.

2.2 Volvo Trucks and its business

In this chapter, Volvo Trucks and its current business characterized as product sales are first presented, followed by an exploration of the likely changes for future PSS business. A PSS-based business has not occurred in Volvo Trucks yet and no exact plans for such a business are set up. What a PSS-based business would be like is unclear, so the likely changes described in relation to such a business are resulted from the exploration through interviews with Volvo employees, in a case that Volvo Trucks sells transportation capacity rather than trucks through leasing business and retains trucks ownership for the whole lifetime. Data used in the following part are collected through interviews unless otherwise noted.

2.2.1 Volvo Trucks

Volvo Trucks is one of the largest heavy-duty truck brand in the world today, owned by Volvo Group. As a world-leading truck manufacturer, Volvo Truck is committed to providing sustainable transport solutions for the fulfillment of their customers' needs. Volvo has been long in efforts for the improvement of corporate performance in economic, social and environmental dimensions. Not only has customer satisfaction been one of the most important concerns for them but also care for the environment has been among their core values besides quality and safety. Technology and science have been in their beliefs used to cope with various challenges facing them and their products. They have demonstrated their strengths in approaching corporate sustainability. Volvo Trucks has the ambition to advance their business towards a less environmentally impacting one and continue to decrease the carbon footprint of their products. (Volvo Trucks, n.d.a)

2.2.2 Volvo Trucks' current business

Volvo Trucks is operated based on a business model of product sales. It sells trucks and offers truck-supporting services on the market in over 140 countries globally through more than 2300 dealerships and workshops (Volvo Trucks, n.d.a). Volvo Trucks' business is primarily focused on sales of trucks, and aftermarket products and services, etc. The aftermarket business stands for the majority of the income of the company at present, while trucks and workshops are the primary contributors among others. Trucks are the core products for sales in Volvo Trucks' business. Volvo Trucks offers truck rental in addition to trucks sales. It is rising but makes up a rather small share of the overall business.

Core products - trucks

Volvo Truck provides a variety of trucks manufactured by them for the application of long-haul transportation, regional and city distribution and construction to their customers. Volvo Trucks has a dozens of truck series for sale on the global market, but the products sold in North America and global market except North America are completely different. The trucks available in Europe are categorized in six series, which are FH, FH 16, FMX, FM, FE and FL as is shown in Table 1. (Volvo Truck, n.d.b)

Table 1. Truck series and their applications

	Applications
FH	Long-haul, regional distribution and construction
FH 16	Long-haul, construction and heavy duty transport
FMX	Construction
FM	Regional distribution, distribution, construction and auto transport
FE	Regional distribution, city distribution, light construction and waste and recycling transport
FL	City distribution, light construction and waste and recycling transport

Among the diverse options of trucks, Volvo Truck offers assistance to customers in configurations and selection of a fleet and a truck. Customers could choose to either buy standard trucks or customized trucks according to varied transport needs. They could also propose components for trucks configuration. Volvo Truck eventually manages to formulate the optimal solution for customers based on customers' transport needs.

Spare parts and exchange program

Spare parts sales play an important role in Volvo Trucks aftermarket business. Volvo Trucks provides customers with genuine Volvo spare parts that represent high quality, including both new and remanufactured ones. Remanufactured components are increasing on aftermarket business. To approach remanufacturing, Volvo Trucks has initiated an exchange program that customers can exchange an old component for a remanufactured one. It is known that the remanufactured components have the same or even better quality due to the application of updated technology compared with the new one, but at a lower price than buying a new one. Therefore, customers have the economic incentive to participate in the exchange program. Through this program increased cores, that are old parts dissembled from trucks, for remanufacturing have been collected back. As a result, remanufacturing business has been in progress. Nevertheless, remanufacturing still accounts for a small share of their aftermarket business at this moment. Due to lack of remanufactured components as a result of insufficient reverse flow of cores, components provided to customers through the exchange are in some cases new ones, not remanufactured.

Volvo Trucks has a long list of components for exchange, but not all of them have been going to remanufacturing for the time being. Only six components, according to the interviewees, are remanufactured, including engines, transmissions, final drives, diesel particulate filters (DPF), rechargers and driers. The other components in return through the exchange is sent for recycling.

Maintenance and workshop services

Volvo Trucks provides maintenance services for customers to improve truck performance and to enhance their use experience of trucks. The key to the performance of trucks from customers' perspective is the guarantee on **uptime,** the working time of truck available for users, which could be achieved through maintenance. Two sorts of maintenance services are offered by workshop. One is **corrective maintenance**, known as repairs of trucks to bring them back to work when they break down. The other is **preventive maintenance** that is performed on planned time-based or driving distance-based schedule to prevent the breakdown and failure of trucks. Through these maintenance services, trucks are kept in good conditions with prolonged useful life and higher uptime are acquired. Moreover, the term of **technical interval** is the maintenance schedule in both preventive and corrective maintenance. Three types of contracts, golden, silver and blue (see Table 2) are provided for customers to choose for the maintenance of their trucks. Usually, maintenance services are contracted along with trucks sales. They do not cover the entire lifetime of trucks, but only last a few years. In a normal case, maintenance services contract is costly for a truck older than five years old due to more unplanned breakdown and increased needs for maintenance.

Table 2. Maintenance services contracts

Contract types	**Services content**
Golden	Maintenances both preventive and corrective for the whole truck
Silver	Preventive maintenance for the whole truck
Blue	Only preventive maintenance for engines

To assist maintenance, information technologies for diagnostics have been applied for quick detection and fixation of problems which enables trucks' uptime to increase. With remote diagnostics, workshops can even find problems before trucks come into the workshop. As a result, corrective maintenance time is further brought down.

Other supportive services

Among other services of Volvo Trucks are fleet management, fuel advice, driver training, etc. They are provided to assist customers in planning their truck operation in an optimal way and facilitating eco-driving and fuel savings. These are value adding services for customers.

2.2.3 Envisioned changes in future PSS business

In the case of truck leasing, Volvo Trucks no longer end their responsibility for trucks after the transaction with the customer, but take care of the trucks throughout their entire lifetime. Perceived to happen is the extensive application of information technologies and telematics for monitoring according to the interview with a Volvo employee. These technologies enable trucks in operation to be under the control of Volvo Trucks, they can collect information on the trucks in use and use this when approaching product development. It also allows all the trucks for leasing to have access to high-quality services provided by Volvo Trucks today including both maintenance and other supportive services. Moreover, with the assistance of telematics, more services could be upgraded to higher levels and more values could be created for customers. Volvo Trucks are incentivized to offer improved services. A change likely to come true regarding service upgrades is the introduction of predictive maintenance to replace preventative maintenance. The **predictive maintenance** is scheduled and implemented, when the failure is predicted to happen based on monitoring of truck usage. The resultant effects are less breakdown for trucks, increased uptime and a reduction in cost critical to customers in the leasing business. To be able to implement predictive maintenance, it requires sensors to be installed on components and parts.

Apart from changes in services provision, change is sure to occur in the aftermarket business. In a leasing business, spare parts sales are no longer a part of the profitable business but counted as costs. Remanufacturing is therefore likely a solution enabling cost reductions. Considering all cores get back to Volvo Trucks in the leasing business, remanufactured components are supposed to have a dramatic growth in number that will drive the development of the circular business.

In addition to the various services provision mentioned, some changes related to product development have been discussed. Designing of lighter weight trucks, e.g. made from carbon fiber or aluminum, is of the corporate interest in order to save fuel because the heavier a truck is, the more fuel is consumed. Moreover, design for maintenance and design for remanufacturing allow the integration of products and services through which the products are adapted to maintenance and remanufacturing.

3. Method

3.1 Research Method

The study has gone through two phases, scenario setting and environmental assessment. To assess the impacts of Volvo Trucks business associated with their products and services, LCA as a product-oriented method has been chosen among a number of environmental assessment tools because it is a verified method for assessing environmental impacts of products and services as Baumann and Tillman (2004) indicate. In this LCA study, GaBi as a world leading LCA software has been applied for LCA modeling. Data required for the scenario setting and the LCA study are partly offered by Gabi databases and previous LCA studies performed by Volvo. Lacking data are further collected through interviews with Volvo employees, from several departments, as well as through a literature review.

3.2 Interviews

The LCA study was carried out to assess the environmental impacts of two business model, the existing business and a hypothetical PSS business. Two business models were explored prior to the environmental assessment. Three questions were investigated for the scenario setting as follows.

- What is Volvo Trucks' business model operated at present like?
- What services or engineering activities would likely be adopted if Volvo Trucks decides to move their business model to PSS?
- What changes could happen in different life cycle stages, e.g. production, use and end of life management?

To be able to answer these questions, interviews were decided as the main strategy for data collection. Several departments within Volvo relevant to the investigation of the issues above were identified, including aftermarket sales, remanufacturing, maintenance, emerging technologies and innovation and rental business. A total of seven employees from these departments were then contacted for interviews.

All the interviews were performed through three steps. They started with a formulation of questions for each interviewee in the pre-interview stage, followed by formal interviews for collecting data and ended up with data analysis. Semi-structured interviews were employed, and for each interview, guide and questions were prepared to remind researchers what to investigate. In general, these interviews centered on a few subjects including estimation on the possible changes on engineering activities and service provision and quantitative improvements regarding the changes as follows.

- Would design for customization, remanufacturing, reuse, and maintenance etc. change? Would those changes affect resource use, fuel consumption, and trucks configurations? Would lifetime of trucks design change?

- Would fleet size be required for the service provision change?
- Would services provide for leasing trucks change? How would this affect trucks' lifetime, uptime, maintenance work (preventive and unplanned) and fuel consumption?
- Would information technology and telematics be applied? How would this affect maintenance work and truck operation? Would this lead to improvement of driving behavior and in turn decrease fuel consumption?
- How would remanufacturing, reuse, recycling be performed? To what extent could they be implemented? How large a share of the components recovered could be remanufactured? What would reverse logistics be presented?

These interviews were conducted in approximately 1-hour time slots. Among all these interviews, five were face to face, one was via Skype, and another was by email. All the face to face interviews were recorded and transcribed. After the analysis based on transcribed data, two likely changes regarding maintenance and remanufacturing among a number were chosen for the scenario setting.

3.3 Life Cycle Assessment

LCA is specifically a systematic and comprehensive approach to evaluating the environmental impacts of products throughout their lifecycle. An LCA model usually consists of lifecycle activities of products from the cradle to the grave, including raw material extraction, production, use and waste treatment. All these activities in different lifecycle stages are supposed to be investigated to quantify the impacts associated with natural resource consumption and environmental emissions yielded in the major industrial systems. LCA is set to focus on the whole industrial systems related to the full lifecycle of products rather than just a few processes in isolation. (Baumann and Tillman, 2004)

In performing an LCA, a four-phase procedure is prescribed according to ISO 14040, which are goal and scope definition, inventory analysis, impact assessment, and interpretation respectively. (Baumann and Tillman, 2004)

The goal and scope definition is of paramount importance for all the other phases in LCA. In this phase, the goal and scope of the study are required to be clearly described. The purpose of the study, its intended application, the targeted audience to communicate with and the product to be studied are stated. Several essential parameters must further be specified to make clear the extent to which the details of LCA model are going to be investigated in the study. The parameters to be defined include functional unit as a quantified expression of a product, system boundaries, allocation, impact categories, data quality requirements, assumptions, and limitations. (Baumann and Tillman, 2004)

After the goal and scope definition, inventory analysis is performed to find out the environmental loads of the product system. It starts with the construction of a system model consisting of activities throughout the lifecycle of products according to the defined system boundaries. This lays a foundation for inventory analysis. In this phase, data relevant to these concerned activities are gathered, including raw materials, energy use, and emissions released into the surrounding environment. These collected data are then calculated according to energy and material balance to map out the inputs and outputs of all the activities about the functional unit. An issue complicated in the inventory analysis is the allocation of environmental burdens to a variety of materials or products in certain multi-input or multi-output process. These are proposed to be dealt with by several allocation methods, e.g. system expansion and partition based on weight, physical properties, and economic values. (Baumann and Tillman, 2004)

The subsequent phase is impact assessment. The inventory results are translated into potential environmental impacts in this phase. It is done through a few steps. Classification is the first step taken through which the inventory results are sorted and assigned to the impact categories specified in the goal and scope definition. It is followed by characterization. During characterization, the contributions of material consumption and emission within each category are quantified and then aggregated into one single number for each impact category. The numbers calculated for each category can then be further aggregated into one single indicator through weighting based on a number of weighting principles, e.g. willing-to-pay, distance-to-target and expert judgment. Different results are supposed to be yielded when different methods are employed that reflect diverse cultural perspectives and values concerning environmental issues. Of these mentioned steps, classification and characterization are mandatory for impact assessment, but the weighting is optional. Whether weighting is needed or not is up to the intended application and the audience. (Baumann and Tillman, 2004)

It finally comes to interpretation, a process to analyze and assess LCA results so as to draw conclusions. Vital findings based on environmental concerns in the LCA are generated in the analysis of results, e.g. the activities that cause significant environmental impacts and the emissions with most contribution to environmental pollution, etc. Some analyses e.g. sensitivity analysis are often used to investigate the robustness of the results. It is noted that the evaluation of data quality and methodological selection on the results need to be made. (Baumann and Tillman, 2004)

4. Goal and Scope

4.1 Goal

The purpose of this study is to assess the potential environmental impact of Volvo Trucks' products and the associated service provision under a PSS business model and compare this to the traditional sales model. Two typical services, maintenance and remanufacturing have been studied closer to emphasize the environmental impact variations and potentialities in the PSS model.

4.1.1 Research questions

In order to reach the goals, research questions have been formulated to focus the aim and track the progress. Questions to be answered are:

- Which business model, PSS or traditional sales, will have better environmental performance for Volvo trucks?
- How can the service changes affect the environmental impacts for the two business models?

This study is commissioned by Volvo Trucks for learning and possibly strategy planning. The intended audiences are Volvo Group Trucks Technology, and Environmental System Analysis unit of Energy and Environmental Department, Chalmers, as well as anyone interested in business models for improving environmental performance including Mistra REES partners.

4.2 Scope

Volvo Group has a variety of operations with unique brand-specific characters in order to attract worldwide customers with different demands. Formation of the brands of Volvo's markets includes Volvo, UD, Renault Trucks, Mack, Eicher, and Dongfeng. (Volvo Group, 2015). Only the trucks under the brand Volvo have been considered in this study. Volvo classifies their trucks into four categories: long-haul, regional distribution, city distribution and construction trucks. The information gathered from the interviews show that Volvo FH series are the representative type of long-haul trucks with the best sales in the market. Therefore, Volvo FH series is the only type of truck assessed in this study.

Volvo Group Trucks Technology has already performed an LCA on an FH series truck. The results of the LCA study are confidential and have not been made public. However, the present study uses the existing FH truck LCA as a blueprint, but focusing on a fleet of trucks instead of one truck, and mainly making changes in maintenance and remanufacturing phases. For this reason, the life cycle inventory results and emissions in one FH truck LCA study will not be elaborated but showed through a fleet in this study (see details in Appendix 1, 2, and 3).

For the business model, a linear model has been set from material extraction to end-of-life (cradle to grave) to describe Volvo's traditional sales model. We assume the prerequisites that Volvo sells trucks, and customers have full ownership of the trucks. Maintenance is included in the traditional sales model, which is carried out in the first five years of the trucks life by Volvo and subsequently by the customers themselves (see details in section 2.2.2). Volvo's remanufacturing business is rising in recent years, but it accounts for only a small portion of Volvo aftermarket business. Remanufacturing is therefore not included in Volvo's traditional sales model.

The PSS model is established with the support of interviews (see details in section 3.2). The assumption during the interviews was that Volvo sells function and retains trucks ownerships during the entire truck lifecycle in product-services system model. According to the interviews, maintenance and remanufacturing are the two biggest possible service changes interviewees forecasted in the PSS model that show the vast potential of development and market fit. For that reason, changing maintenance and adding remanufacturing were two principal research objects presented in the PSS model. Because of the time constraints and the difficulties in data collection, only engines (D13) used in FH series trucks have been considered for remanufacturing in this study.

Thus, this study is to assess the potential environmental improvements from maintenance changes and remanufacturing engines for FH series truck between traditional sales model and PSS model.

4.2.1 Functional Unit

This study is formulated based on fleet thinking. Normally, the functional unit (FU) used in Volvo Trucks LCA studies is the lifelong driving distance, but the function for a fleet is appropriately set as transport capacity in kg ·km. As there would be no changes in regards to load capacity of a truck in the two business models, the transport capacity will be proportional to the driving distance. The functional unit could therefore be simplified as transport measured in km. According to Volvo, the FH long-haul truck's annual driving distance on average is estimated approximately as 10^5 km. A fleet of 1000 FH trucks, with 100% uptime, can provide 10^8 km per year as function. In that case, 10^8 kilometers in one year (km/yr) is set as the functional unit (FH) in this study for a fleet to accomplish.

4.2.2 Type of LCA

As the LCA in this study is based on Volvo's existing FH truck LCA study, an accounting LCA has been chosen. Moreover, although the product-services system model has not been implemented in Volvo, the scenario setting in the PSS model referring to maintenance changes and remanufacturing are based on Volvo’s available capacity. The data chosen in this study determines a move towards a comparative accounting LCA.

4.2.3 System Boundaries

This study is to explore the environmental impacts of the transportation capacity to be fulfilled by a fleet in a year. As is explained in fleet calculation and scenario setting (chapter 4.2.4), the total environmental impacts caused by the fleets in a year are converted to the impacts resulted from the lifecycle impacts of trucks that need to be replaced each year.

This study looks at the full life cycle of the trucks from the cradle to the grave, from material extraction, through manufacturing of parts and components, assembly of trucks, and use finally to end of life management. Between every phase there is transportation as well, except directly following assemble, as it is assumed that trucks can be directly driven after the completion of their assembly. Also, transport certain to happen in post-sales phases is related to reverse logistics for remanufacturing of engines. Concerning the use phase, a few processes are highlighted and investigated, including maintenance, fuel consumption that contains processes of crude oil extraction and diesel production, tailpipe emissions and remanufacturing.

Time and geographic boundaries

The time boundary for this study is set to be one year as defined in the functional unit. It is then converted to the life cycle impacts from replacing the required trucks in a year. The fleet is defined as a combination of trucks with even age distribution as is explained in section 4.2.4. Its year of operation is assumed to be in 2016. The environmental impacts of the fleet then correspond to the newly manufactured trucks that are purchased in that year in order to replace outgoing trucks. Those replacement trucks are manufactured and sold in 2016, and they will be dismantled and treated in 2026 (under the product sales scenario) and in 2036 (under the two PSS business scenarios). This study compares the existing business model to possible future PSS business models and explores the potential environmental improvements and trade-offs. The investigation of the existing business is retrospective while the PSS scenarios are prospective. The data for the processes and technologies in the first scenario is based on a previous LCA report and the other scenarios are built on this foundation.

The transportation function fulfilled by the fleet as defined in functional unit is assumed to take place in Europe. It refers to the use phase of these Volvo trucks. The trucks are therefore used and maintained in Europe. However, materials consumed for truck manufacturing are assumed to be from all over the world. Component and truck manufacturing, as well as End of Life treatment, takes place in Europe as explained in inventories.

4.2.4 Fleet calculation and scenario setting

In order to make comparisons between the two business models, three scenarios are set according to the information gathered from the interviews. Based on the functional unit (10^8 km/yr), a fleet of FH trucks is set as the unit of analysis in each scenario.

The number of trucks needed to fulfill the function

The fleet is defined as being composed of a number of long-haul FH trucks with an even age distribution fleet, from new to retiring (EoL) trucks. The number is dictated by the functional unit (10^8 km/yr), and every year there are a number of trucks that approach their end of life and need to be replaced. The calculation of the number of trucks needed in the fleet relates to two parameters, namely the truck's lifetime and uptime.

The lifetime of the trucks is key to the composition of the fleet. It determines how many groups of trucks the fleet is divided into, and further affects how many trucks in each age group that need to be replaced. For example, if the fleet has 1000 trucks and the lifetime of one truck is 10 years, then the age-distribution of the trucks is assumed to be arrangement as showed in table 3 below. To maintain the fleet 100 trucks, need to be replaced each year, and the number of 1/10 is defined as the replacement rate.

Table 3. An example of the even age distribution of trucks in the fleet

Age (yr)	1	2	3	4	5	6	7	8	9	10
No. of the truck	100	100	100	100	100	100	100	100	100	100

The other variable, uptime, determines the total number of trucks required to fulfill the needs for transport and whether a number of extra trucks are needed to fulfill the customers' needs. For instance, if the average uptime of the trucks is 80% instead of 100%, then the 1000 trucks shown in table 3 are not capable of providing the transport defined in the functional unit and some extra trucks are needed because FH trucks are available for only 80% of time when they are needed. In this case, a total of 1250 trucks are needed to fulfill the functional unit, and the 250 additional trucks are called substitution trucks.

As mentioned, the number of replaced trucks is affected by both lifetime and uptime. It can be calculated according to the functional unit defined in this study (10^8 km/yr). The total environmental impacts of the fleets can thus be calculated by multiplying the number of trucks to be replaced each year with the environmental impacts of a single FH truck, for each scenario.

The parameters used in the fleet calculation are shown as follows:

- Function defined in Functional unit: X [10^8 km/yr]
- Annual driving distance, i.e. the annual transport provided by one truck: A [10^5km]
- Uptime: U [%]
- Lifetime of a FH truck in year: L [years]
- Environmental impact of one FH truck from production to end-of-life (excluding the fuel use): E [ELU]
- Environmental impacts of the replaced trucks from production to end-of-life (excluding the fuel use) per year: I [ELU]

The fleet calculation has three steps: 1. calculating the number of trucks in the fleet; 2. calculating the number of trucks that need to be replaced because they reach the end-of-life; 3. calculating the environmental impacts of new replacement trucks

1. No. of trucks needed in the fleet: $\mathrm{T} = \frac{\mathrm{X}}{\mathrm{A} * \mathrm{U}}$

The total number of trucks needed in the fleet in order to fulfill the functional unit is calculated by dividing the functional unit X with the annual driving distance that each truck achieves, A, multiplied by the uptime, U.

2. No. of replaced trucks per year: $N_{replaced} = \mathrm{T} \cdot \frac{1}{\mathrm{L}} = \frac{\mathrm{X}}{(\mathrm{A} * \mathrm{U}) * \mathrm{L}}$

The number of replaced trucks each year in the fleet in order to fulfill the function is calculated by the number of trucks in the fleet times the replacement rate, $\frac{1}{\mathrm{L}}$. (or divided the trucks lifetime, L).

3. Environmental impacts of the replaced trucks per year: $\mathrm{I} = N_{replaced} * \mathrm{E} = \frac{\mathrm{X}}{(\mathrm{A} * \mathrm{U}) * \mathrm{L}} * \mathrm{E}$

The environmental impacts of the replaced trucks from production to end-of-life (excluding the fuel use) each year is equal to the number of replaced trucks needed in the fleet each year times one truck's environmental impact, E.

The formulas indicate the total impacts of the fleet determined by several parameters, for example, the transport defined in the functional unit, lifetime, uptime, annual driving distance and a truck's environmental impacts. The functional unit and annual driving distance are constant, while the others are variable. The number of replaced trucks needed in the fleet is controlled by the trucks lifetime and uptime. The higher lifetime and uptime the trucks can maintain, the less replacement trucks are needed each year.

Scenario setting

The three scenarios in this study are the traditional selling model, the PSS model including a change in maintenance and the PSS model including remanufacturing, respectively.

The parameters for the three scenarios are chosen according to the information gathered from interviews (table 4). The annual driving distance for an FH truck is around 10^5 km. The lifetime of FH trucks in the Volvo system is assumed as 10^6 km, and the expectation for the future designing requirements of FH trucks is $2 \cdot 10^6$ km. In this study, we assume the lifetime of FH truck in traditional model keep the same with Volvo existing model ($1 \cdot 10^6$ km), and the lifetime extends to FH truck designing time ($2 \cdot 10^6$ km) because of the better monitoring and the maintenance in the PSS model.

Normally, the uptime that customers can accept is had to be tracked. According to the interviews, typically a Volvo customer can expect an uptime between 93 and 97%, uptime of 95% in the first five years of FH trucks life is assumed acceptable for Volvo customers. After five years, the trucks are possible to be sold to the second owners and the details are more uncertain for Volvo. Therefore, an assumption of 75% is set as the uptime for the second five-year period for FH trucks, and consequently the average uptime in the traditional model is 85%. With the gold contract services, as described in section 2.2.2, Volvo can guarantee the uptime of their trucks up to be approximately 100%. This condition of 100% uptime is assumed to be continued in the PSS model, for the entire lifetime of each truck.

In reality, customers keep 5 years’ maintenance cooperation with Volvo and after 5 years, the owners do the maintenance by themselves. Such a situation is unlikely in the PSS model, as it is assumed Volvo will keep maintaining the trucks over their entire life. The only part of the truck considered to be remanufactured is the engine D13, and it is assumed to be remanufactured twice. Scenario 2 and 3 share the same maintenance activities, and scenario 3 further includes the remanufacturing of engines in addition to the changes in maintenance.

Following with the calculation steps in the fleet calculation above, the traditional model needs to replace 118 trucks each year, and in the PSS model, the fleet needs 50 replaced trucks in both scenario 2 and 3.

Table 4. The parameters for the three scenarios

	Scenario 1	**Scenario 2**	**Scenario 3**
Model	Traditional sales model	Maint.in PSS model	Reman. in PSS model
Function delivered	10^8 km	10^8 km	10^8 km
Annual driving distance per truck	10^5 km	10^5 km	10^5 km
Lifetime (years)	10 years	20 years	20 years
Lifetime (km)	10^6 km	$2\cdot10^6$ km	$2\cdot10^6$km
Uptime	85%	100%	100%
No. of trucks needed in the fleet	1180	1000	1000
No. of replaced trucks per year	118	50	50
Maintenance	5 yrs Volvo maint.+ 5 yrs self-services	20 yrs Volvo maint.	20 yrs Volvo maint.
Remanufacturing	No	No	Engine reman.

4.2.5 Life cycle Flow Chart

Figure 1 and 2 show the simplified flowcharts of the life cycle according to the scenarios. In Figure 1 is showed scenario 1 (the traditional sales model) and scenario 2 (maintenance in the PSS model) share the same flowchart. However, the number of replaced trucks in the two scenarios are different, 118 in scenario 1 and 50 in scenario 2, respectively. Considering the remanufacturing phase, the flowchart in scenario 3: remanufacturing in the PSS model (figure 2) shows differences after the trucks reach the end-of-life. The old engines in the system go through remanufacturing twice and ultimately go to waste disposal.

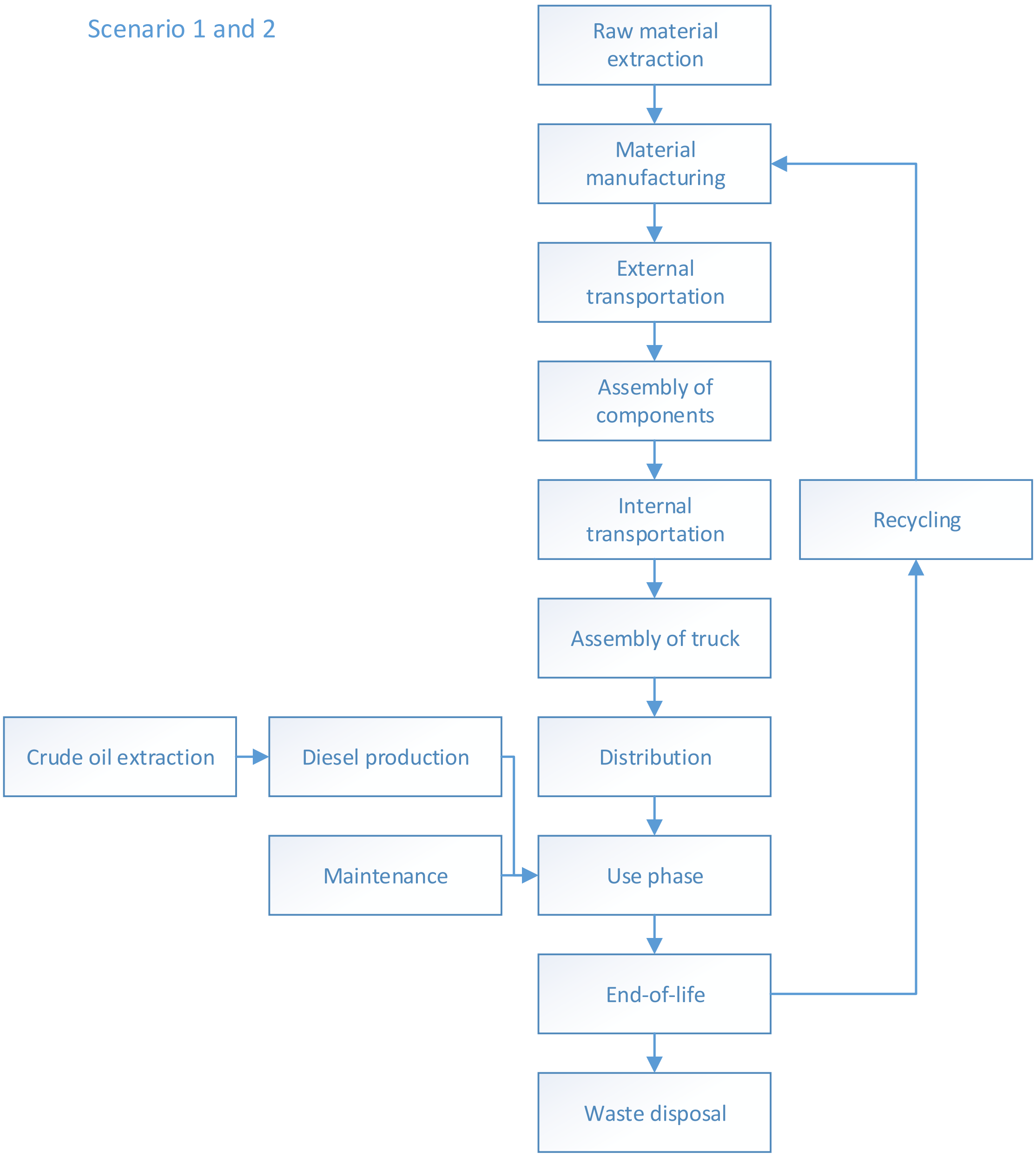

Figure 1. Flow chart for scenario 1 and 2.

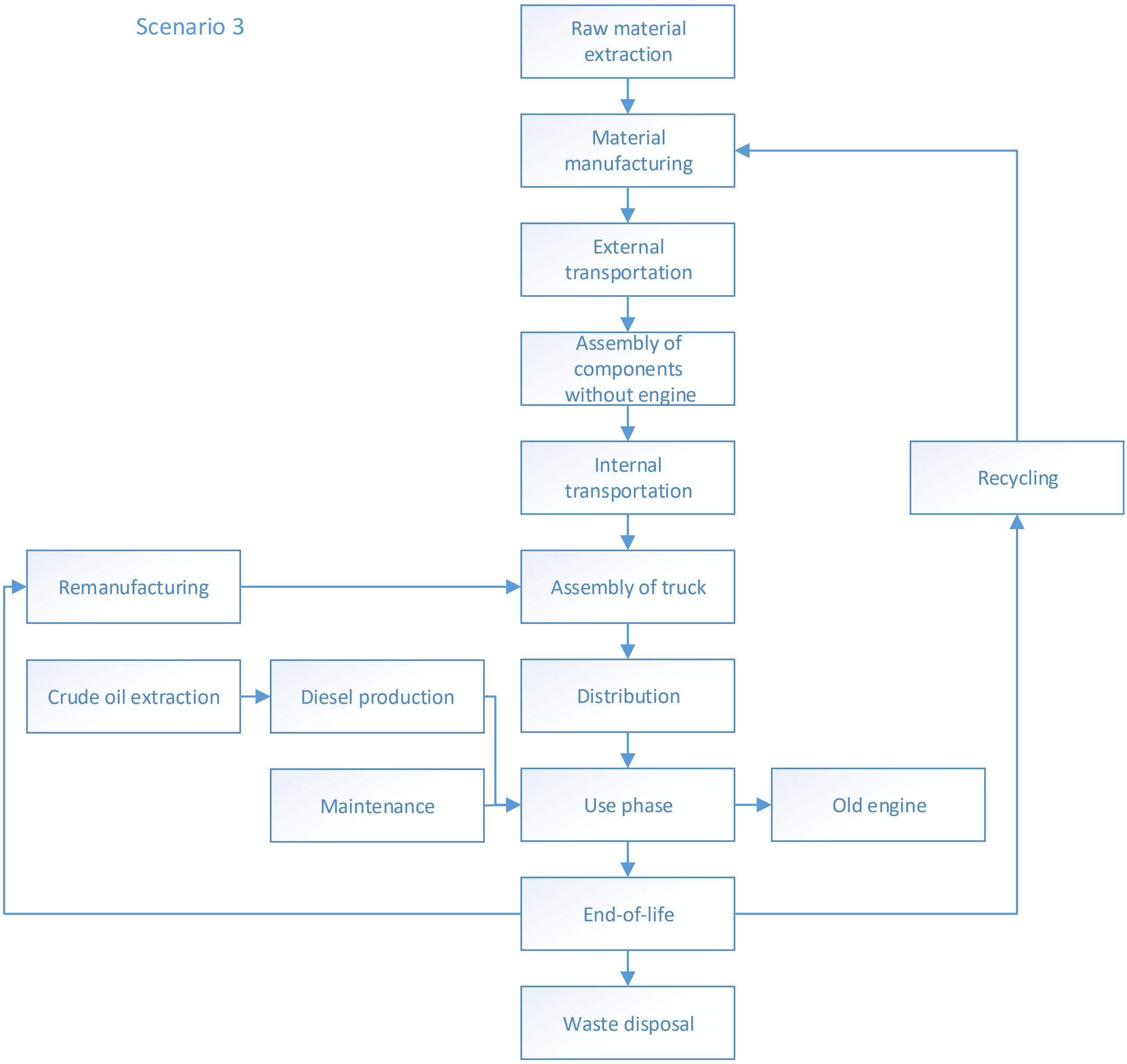

Figure 2. Flow chart for scenario 3 including remanufacturing.

4.2.6 Impact categories

Because they are the most relevant impacts categories for truck manufacturing companies in the automotive industry, four impact categories have been selected in this study. Respectively, they are Global Warming Potential (GWP), Abiotic Resource Depletion Potential (ADP), Acidification Potential (AP), and Human Toxicity Potential (HTP). The choice is according to the recommendation in the ILCD handbook (Joint Research Center – Institute for Environment and Sustainability, 2010).

Global Warming Potential

The Global Warming Potential (GWP) in a 100 years' perspective is calculated in CO2-equivalents.

Examples of substances contributing to GWP are carbon dioxide, methane, and nitrous oxide. GWP is one of the commonly used indicators in assessing products from the environmental phase. Global warming is a worldwide problem, and in an automotive context, it is an inevitable indicator.

Abiotic resources depletion potential

The Abiotic Resource Depletion Potential (ADP), also called RDP, is calculated in Sb-equivalents (antimony). The indicator reflects the use of non-renewable substances, which could eventually lead to resource depletion. Examples of materials that contribute a lot to this potential are gold, silver, platinum and fossil fuels. The abiotic resources depletion potential is needed to be included in this study because the scarcity materials used in the production phase, for example, platinum and palladium used in muffler and gold and silver used in electrical equipment.

Acidification Potential

Acidification Potential (AP) is calculated in SO_2-equivalents. The important substances that contribute to lowering the pH-value in soils, water and ecosystems are ammonium, nitrogen oxide etc.

Human toxicity potential

Human toxicity potential is measured in Comparative Toxic Unit for humans (CTUh). The substances contributing to this potential are cadmium, arsenic, and dioxins. Long-haul trucks are traveling between the cities and streets, and the traveling of trucks affect people's living environment.

4.2.7 Weighting method

Weighting method is a method that transform the overall environmental problems and emissions into a single scale. Different weighting methods reflect different social values and preferences under different weighting principles. This study concentrated on EPS weighting method for showing the impact assessment and following with ReCiPe weighting method in sensitivity analysis as comparisons for final environmental results.

EPS 2014

The Environmental priority strategies (EPS) system is a systematic weighting method that focuses on product design and process development. The system has been used by Volvo for more than 25 years. EPS is developed based on the willingness to pay principle, which is how much the society is willing to pay to avoid a certain environmental load. Environmental Load Units (ELU) is a unit used in the system to measure the impact of emissions and resource extraction on a common scale. This study aims to make comparisons of the environmental impacts of the fleets configured for different business models. EPS gives a high priority to materials in weighting the environmental burdens. with the strategic connotation of circular economic thinking and resource efficiency in Volvo’s products. EPS is able to assist product developer in make a quick decision on their choice of materials in product development. It produces a rather clear index in a straightforward manner which can help the audience to comprehend the results of the study.

ReCiPe

ReCiPe weighting system is used in the sensitivity analysis, to yield alternative results for all the three scenarios, which are then compared with the original results generated by EPS. The weighting results are shown in Sensitivity analysis (7.7).

According to Gabi software, ReCiPe is viewed as a methodology with the combination of CML and Eco-indicator 99, taking the midpoint indicators from CML and the endpoint indicators from Eco-indicator. It has three different versions of the modelling of the environmental mechanisms. Each reflects a cultural perspective which represents a set of value choices regarding human-nature relations, these three cultural perspectives are illustrated below.

- Individualist (I) perspective concerns over the short term environmental impact based on the rationales of technological optimism that humans are capable of solving the problems with the technological development in the long run. The time frame used is short, e.g. a 20-year time frame for global warming GWP20.
- Hierarchist (H) perspective adopts a set of moderate values that are commonly applied in environmental policies. Time frame used is medium, e.g. a 100-year time frame for global warming, GWP100.
- Egalitarian (E) perspective focuses on long time environmental mechanism due to an emphasis on the fragility of nature. It therefore is more precautionary than the other two perspectives. Time frame used is the longest one, 500-year time frame for global warming, GWP500. (Goedkoop M.J. et al., 2013)

Hierarchist perspective is decided to use in this study according to the recommendation of the ILCD handbook.

5. Inventory analysis

The inventory analysis illustrates the processes of FH trucks life cycle, data collection, calculation, and modeling. As is clarified, this study is built on the FH truck LCA study previously done by Volvo and the major changes in the PSS business are investigated in relation to two activities, maintenance and remanufacturing， and in this study, we focus on maintenance and remanufacturing.

According to the Volvo existing study, the whole life cycle of FH truck can be classified into three phases, production, use phase and end-of-life. Three scenarios share the same three phases; however, only the third scenario includes one more phase, remanufacturing phase (Table 5). Production phase includes material and manufacturing. The meaning of material is the production of raw materials, and manufacturing can be defined as the process of material refining and truck assembling. Use phase includes fuel consumption and maintenance phase, which con be considered as diesel combustion and preventive and corrective maintenance. When FH truck reaches to its lifetime, truck needs to be scrapped. End-of-life is the phase after scrapping, such as landfilling, incineration and recycling. The only engine has been remanufactured in this study, the remanufacturing phase in scenario 3 includes engines life cycle, material changes in remanufactured engine, energy use, transportation and also material end-of-life. The Inventory results and environmental effects in three scenarios have been shown in Appendix 1, 2, and 3.

Table 5. Life cycle phases of FH truck

Life cycle	Scenario 1	Scenario 2	Scenario 3	Data sources
Production	Material	Material	Material	Bill Of Material (BOM)
	Manufacturing	Manufacturing	Manufacturing	Energy use Transportation
			Remanufacturing	Material Energy use Transportation EOL
Use	Fuel consumption	Fuel consumption	Fuel consumption	Fuel and urea consumption
	Maintenance	Maintenance	Maintenance	Spare parts Technical intervals
End-of-life	EOL	EOL	EOL	Recycling rate

5.1 Production

5.1.1 Material and components

With the help of Volvo IT, a BOM (bill of material) of FH truck was created in existing FH truck LCA study. After simplified and translation, the BOM data were mainly employed in LCA software, Gabi.

The data sources can be sorted into three groups, from the international organization, such as European Aluminum Association (EAA), World Steel Association (IISI), International Stainless Steel Forum (ISSF) and Plastics Europe; from PE International and Ecoinvent; and the data for casting iron are come from the Volvo facilities in Skövde.

In existing LCA study, the FH truck can be divided into 17 parts of components.

Table 6. 17 components in FH truck.

Components number	**Components**
010	Chassis Structure
015	Pneumatic Structure
020	Electrical Structure
021	Electronic Structure
030	Front Axle Installation
033	Rear Axle Installation
036	Wheel, Brake & Hub
040	Chassis Equipment
045	Transport Adaptation
048	Power Train Installation
050	Engine
060	Transmission
070	Vehicle front
080	Cab body
085	Cab exterior
090	Driving
095	Living

5.1.2 Manufacturing

According to the existing LCA study, both Volvo Group manufacturing and non-Volvo Group manufacturing need to be considered. The Volvo Group manufacturing is also called as internal manufacturing and the non-Volvo Group manufacturing is called external manufacturing. Köping for gearbox, Skövde for engine, Umeå for cab, Tuve for frames and truck assembly and Ghent for truck assembly are internal manufacturing plants for Volvo. The data collection on non-Volvo Group manufacturing (external manufacturing) from suppliers or project partners for the LCA study is difficult. Therefore, a double of energy and material consumption for Volvo internal manufacturing is assumed as the total one in the manufacturing phase.

5.1.3 Transportation

The transportation in this study are included in both manufacturing phase and remanufacturing process. The transport data accounted for manufacturing phase between Volvo's suppliers and Volvo's assembly plants were taken from the LCA study of FH truck. The transportation distances in terms of remanufacturing are estimated and calculated based on the average distances on Google map from the typical countries to Flen, one of the Volvo's plants for engine remanufacturing.

The transport in the manufacturing phase have been classified into internal transportation and external transportation. The internal transport represents the transportation going from each of Volvo's plants to the two assembly factories in Tuve and Ghent. The external transport refers to the transportation from different suppliers to Volvo's plants. Besides the two assembly factories in relation to internal transportation, there are another three plants for external transportation and components assembly, which are Umeå, Skövde, and Köping.

Transports of the interior are assumed as transport on land by using trucks only. In this study, the heavy diesel driven truck in line with the standard of the Euro 4 emission regulation has been chosen, which has the average weight of 32 tons and 22 tons' payload capacity. During the operation, this type of trucks is driven in the highway mode and their load capacity are assumed to remain at 85%. The external transportation from other countries in Europe to Volvo's plants is assumed the same as in the internal transportation. The transportation from countries like USA and Brazil is assumed to be carried out by diesel driven freighters with a payload capacity of 2817 tons.

Table 7 shows a list of weights and distances for both internal and external transportation in the manufacturing phase on an aggregated level. The units of distance and weights are expressed as kilometer and kilograms. (Or the distance and weights are accounted in km and kg.)

Table 7. Transportation distances and weights to assembly factories.

Assembly factory		Weight (kg)	Distance (km)
Internal transportation			
To Tuve		1672	1517
To Ghent		2882	6332
External transportation			
To Umeå		2000	12821
To Ghent		2099	5908
To Tuve		2225	6661
To Köping		954.525	3181
	From USA	20,475	10000
	From Brazil	18,525	15000
To Skövde		1413	8141
	From USA	87	10000

5.2 Use phase

Use phase contains fuel consumption and maintenance.

5.2.1 Fuel consumption

The fuel consumption data directly are collected from the FH truck LCA study. The data of diesel consumption and emissions, in terms of FH trucks equipped with the Euro 6 engines (D13), are generated from warehouse test cycle. The diesel used in FH trucks is 0.31 Liter per km and 5.7% of Urea is added in volume.

As the functional unit in this study is transport of $1 \cdot 10^8$ km for three scenarios, and the fuel consumption and emissions in three scenarios are assumed to be identical. (Table 8). In reality the fuel consumption will be different, but this is dealt with in the sensitivity analysis.

Table 8. Diesel use and emission in three scenarios

	Unit	Scenario 1	Scenario 2	Scenario 3
Diesel	Liter	3.10E+07	3.10E+07	3.10E+07
Urea	Vol % added	5.7%	5.7%	5.7%
CO	kg	3.66E+03	3.66E+03	3.66E+03
CO_2	kg	8.15E+07	8.15E+07	8.15E+07
HC	kg	3.10E+00	3.10E+00	3.10E+00
NO_x	kg	1.28E+04	1.28E+04	1.28E+04
SO_2	kg	1.56E+02	1.56E+02	1.56E+02
Particles	kg	2.74E+02	2.74E+02	2.74E+02

5.2.2 Maintenance

Maintenance is another important part in use phase. During the truck use phase, maintenance scheme contains the replacement of materials, fluids and spare parts. It consists of preventive maintenance and corrective maintenance. Part of materials consumed for maintenance are supposed to be recycled, which is modelled in the maintenance processes. Transportation and energy use are not included because of lacking data. The maintenance operation choice has been described in the scenario setting (Detail see section 4.2.4).

Preventive maintenance

As the planned maintenance, preventive maintenance serves to avoid or reduce the failure of truck components. The list of preventive maintenance is from aftermarket department and the project manager. It includes 12 services. Table 9 and 10 show aggregated preventive maintenance material lists in the whole lifetime in three scenarios. Table 9 describes the preventive maintenance materials for Scenario 1 in ten year's period for trucks' operation, an aggregation of the first five years' maintenance implemented by Volvo and the last five years' by customers themselves. Table 10 illustrates a 20-year's maintenance performed by Volvo.

Table 9.Preventive maintenance material list in scenario 1

Material list of Preventive maint. in scenario 1	**Unit**		
Steel	Mass	40.01524	kg
plastic material	Mass	3.787133	kg
rubber material	Mass	0.913845	kg
other metals	Mass	0.251813	kg
other materials	Mass	36.54815	kg
crude oil	Mass	314.1	kg
Total	Mass	395.6162	kg

Table 10. Preventive maintenance material list in scenario 2 and 3.

Material list of Preventive maint. in scenario 2&3	**Unit**		
Steel	Mass	107.9757	kg
plastic material	Mass	14.38208	kg
rubber material	Mass	3.405961	kg
other metals	Mass	0.852155	kg
other materials	Mass	115.66	kg
crude oil	Mass	657.9	kg
Total	Mass	900.18	kg

Corrective maintenance

The data for corrective maintenance can be hard to obtain because corrective maintenance only occurs when truck components fail to operate, or trucks are subject to breakdown. The material lists of corrective maintenance in three scenarios have been shown in table 11 and 12.

Table 11.Corrective maintenance material list in scenario 1

Material list of Corrective maint. in scenario 1	**Unit**		
Steel	Mass	108	kg
plastic material	Mass	334.144	kg
rubber material	Mass	77.87	kg
other metals	Mass	6.880359	kg
other materials	Mass	712.336	kg
crude oil	Mass	480.182	kg
Total	Mass	1719.412	kg

Table 12. Corrective maintenance material list in scenario 2&3.

Material list of Corrective maint. in scenario 2&3	**Unit**		
cast iron	Mass	216	kg
steel	Mass	950.826	kg
lead	Mass	155.74	kg
plastic material	Mass	15.216	kg
rubber material	Mass	1962.4	kg
other materials	Mass	1294.1	kg
Total	Mass	4594.2	kg

5.3 End-of-life

The previous Volvo report shows that metals cause most of the impacts in trucks' end-of-life phase. Only metals and natural rubber have been involved in terms of the end-of-life phase in existing LCA study. It is also assumed that the recovered metals in the end of life phase are recycled to produce the same materials that are used in the manufacturing phase. The metals in the model are recycled under the following rate.

- Metals in electronics are assumed to be recycled at a rate of 50%
- The recycling rate of aluminum, steel, copper and lead is assumed to be 100%.
- Platinum and Palladium is assumed to be recycled at a rate of 97%.
- 80% of Gold, silver and stainless steel was modeled to be recovered as data for their recycling processes are not available.
- The remaining materials are treated as a non-elementary output of waste

The end-of-life treatment of materials used in the maintenance phase and engine remanufacturing remains the same with FH truck' end-of-life.

5.4 Remanufacturing

Only engine D13 is remanufactured in scenario 3. Because of lacking data for remanufacturing, the modeling of a remanufacturing engine has been set up according to the information from the interviews.

5.4.1 Material

Compared with a new engine, about 20% of the materials need to be replaced in a remanufactured engine according to the interviews. The total weight of the D13 engine is 1221.58kg, so the replaced materials weight in the remanufacturing engine is 244.32kg. This study assumes all the non-metal parts in the engine need to be replaced and the rest of weight is shared by cast and wrought iron.

5.4.2 Energy use

According to the interviews, a remanufactured engine uses only 9% of the total energy consumed for manufacturing a new engine. The energy consumption for engine manufacturing is calculated based on weight allocation. Engine D13 occupies 16.5% of total energy consumption in FH truck. 9% of energy used for engine manufacturing is taken as the one for engine remanufacturing.

5.4.3 Transport in remanufacturing

The transportation related to remanufacturing in this study only concerns over the reverse flows of engines taking place in Europe. According to Volvo’s annual report (2015), the largest markets in Europe includes France, the UK, Germany, Sweden, and Norway. In this study, only these five countries are considered for the calculation of the average distances from these concerned countries to Volvo’s remanufacturing factory in Flen, Sweden. The type of engine focused on in this study is model number D13 used in the FH trucks, and Flen is the only remanufacturing plant in the practice of remanufacturing for D13 engines at present. The transport is assumed to be carried out on land by the truck with the same specification as internal transportation in manufacture phase. It is assumed that the same amount of engines are collected from each country for remanufacturing. Table 13 shows the estimated distances from each of the five countries to Flen and the weight of D13 engine collected for remanufacturing in each country.

Table 13. Average distances to Flen and weight of engine.

Country	**Distance (km)**	**Weight of engine (kg)**
France	2167	1221.58
The UK	1467	1221.58
Germany	1232	1221.58
Sweden	204	1221.58
Norway	625	1221.58
Average	1139	1221.58

6. Impact assessment

In order to answer the two questions posed in the goal and scope chapter, four impact categories, i.e. GWP, ADP, AP and HTP, and one weighting method (EPS) have been chosen to interpret the environmental impact changes between business models in this study.

Three scenarios, including traditional sale as reference and the other two related to services (maintenance and remanufacturing) in PSS, have been set to evaluate the environmental improvements.

Based on the fleet calculation and scenario setting (section 4.2.4), 118 trucks in the traditional sales model (scenario 1) and 50 trucks in the PSS model (scenario 2 and 3) need to be replaced respectively. The results of the impact assessment are represented in bar charts. The contrasts between scenario 1 and 2 show the influences from the maintenance, while the differences between scenario 2 and 3 clarify the impacts from the remanufacturing of engines. Maintenance leads to the change in the number of replaced trucks in scenario 1 and 2. Moreover, the maintenance schemes in both scenarios are different. Scenario 2 and 3 share the same number of substituted trucks based on the identical assumptions on lifetime and uptime. The only distinction between these two scenarios (2 and 3) lies in the engines used in the fleet, new engines in scenario 2 and remanufactured engines that can be remanufactured twice in scenario 3.

6.1 Results for each impact category.

The results for the different impact categories are represented in two parts: including and excluding fuel consumption. Because the mileages are assumed to be the same, the fuel use in the result part is assumed the same in three scenarios. The environmental impacts of fuel consumption in the three scenarios remain same, as is shown in the figure below.

Figure 3 describes the environmental impacts of three scenarios in four impact categories considering fuel consumption. The results show that the PSS model is capable of decreasing the environmental impacts compared with the traditional model. The environmental impacts in the PSS model is lower by around 1% in GWP, almost 30% in ADP, 5% in AP and around 4% in HTP, respectively. The disparity of the reduction in environmental impacts among these categories are caused by the different proportions of fuel consumption to the total environmental impacts in each category. The fuel consumption accounts for almost over 90% of CO2 equivalents, SO2 equivalents, and CTUh in GWP, AP, and HTP respectively, and this can explain why the PSS model has a relatively lower environmental impact in these three categories. ADP refers to the use of non-renewable substances, and a major relevant environmental problem is resource depletion. In terms of ADP, the production and end-of-life phases occupy more percentage of impacts and fleet change therefore contribute to a higher environmental impacts reduction in the PSS model compared with the other three categories in which fuel consumption dominate the total environmental impacts.

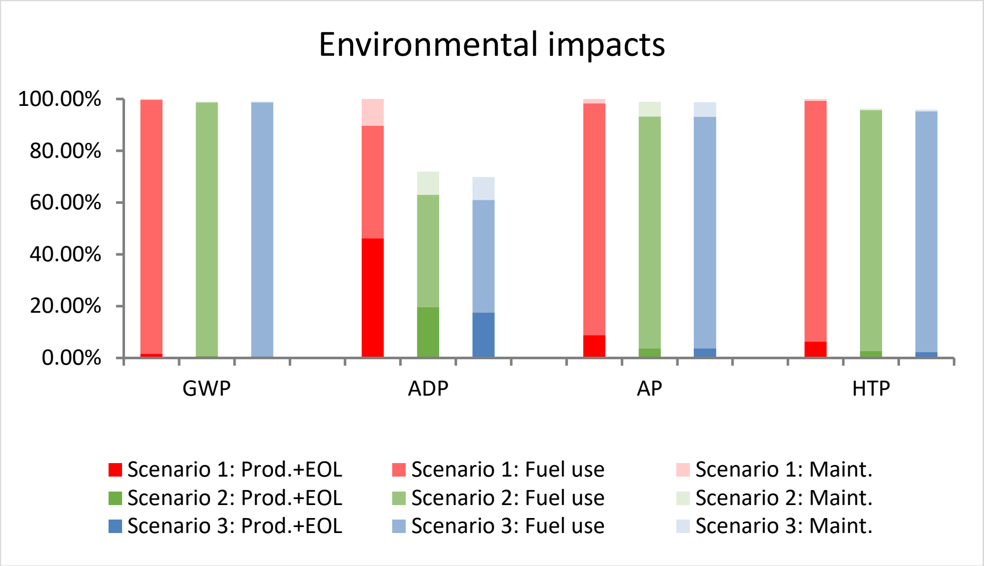

Figure 3. Normalized results for four impact categories (GWP, ADP, AP, and HTP) for trucks production and end-of-life (Prod.+EOL.), fuel consumption and maintenance phase (Maint.) in three scenarios.

It can be relevant to study the impacts excluding fuel consumption. The main reason behind it is that the PSS model in this study is structured based on a future perspective. The fuel consumption is considered less important in the future due to expected fuel technology improvement or even the replacement of diesel trucks by electric trucks. From a long-term sustainability perspective, the resource scarcity would be the most serious problem presented in the truck industry when fuel problems are solved in the future.

As can be seen in figure 4, the results for the four impact categories show similar trends as the PSS model can lower the total environmental impacts by approximately 50% when compared with the traditional model. Maintenance represents 47.5% of the environmental improvement and remanufacturing represents another 1.5% in GWP. The results of environmental impacts in terms of ADP, AP, and HTP show maintenance contributes to 49.6%, 46.3% and 52.4% of the total environmental improvements, respectively. Moreover, remanufacturing can further decrease the environmental impacts in the PSS model by 3.6%, 1% and 6.3%. A result of improving Maintenance in the PSS model is that less trucks are needed compared with the traditional model, which contributes to the majority of the environmental improvements in the four impact categories. The improvements resulting from remanufacturing are smaller because in this study only the engine remanufacturing (no other parts of the truck) are considered and the impacts of engine D13 is only around 5% to the total impacts of trucks.

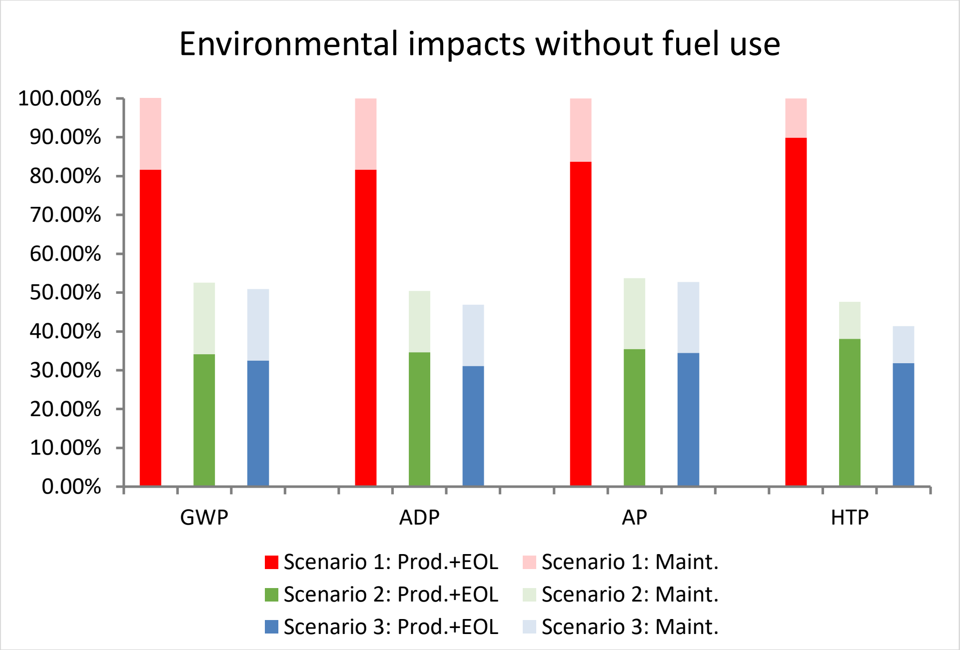

Figure 4. Normalized results for four impact categories (GWP, ADP, AP, and HTP) for trucks production and end-of-life (Prod.+EOL.) and maintenance phase (Maint.) in three scenarios.

6.2 Weighted result in EPS

Figure 5 shows the results generated based on EPS weighting method, describing the comparison of environmental impact between two business models measured in environmental load units (ELU). Scenario 1 in the traditional model serves as the baseline reference for comparisons with the other scenarios in terms of environmental improvements. Fuel consumption still has the biggest impact in the system, taking up almost 80% of total environmental impacts. Production and end-of-life phase account for the rest 20% of the impacts, and maintenance shares only 1% of total impacts. PSS model has the capacity to provide almost 12% of environmental improvements when compare to the traditional model. The improvement brought by maintenance in are 11.7% and remanufacturing contributes further by 0.3%.

Three scenarios in two models share an assumption that the same driving mileage in the use phase is run for three scenarios. It points therefore to the same number of environmental impacts from fuel consumption in all three scenarios as is represented in figure 5. Figure 6 shows the EPS weighting results in three scenarios without fuel consumption phase. It reveals representative results for materials consumption by excluding the environmental impacts from the well-to-wheel impacts of the fuel. The figure 6 shows a decline in emissions by 55.5% is achieved in the PSS model compared with the traditional model. Maintenance contribute to a decline in emission by 54.98% and remanufacturing contributes further by 1.5%. Because of the high weighting on scarce and toxic elements in EPS weighting method, the EPS weighting tends to closer resemble the results shows by ADP.

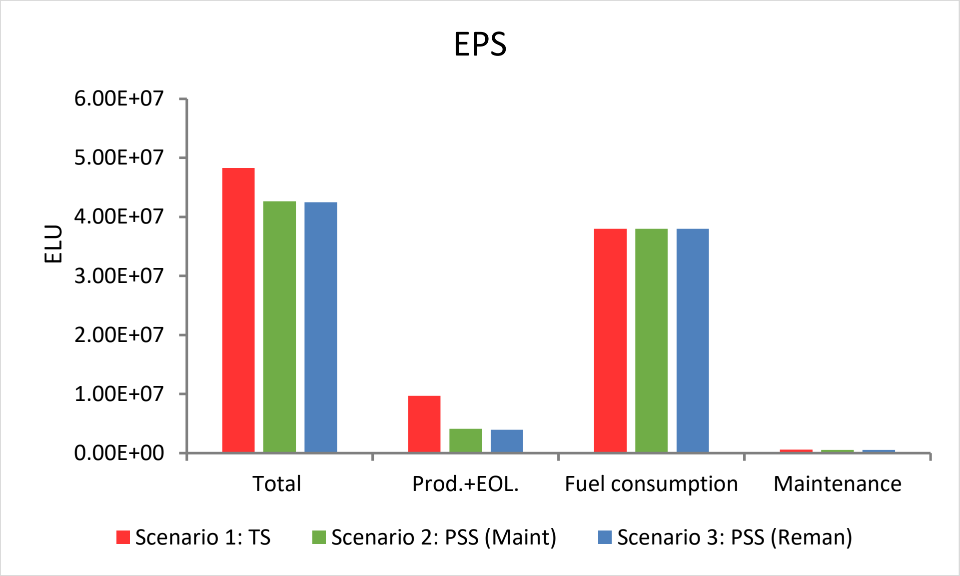

Figure 5. EPS weighting results in ELU for truck production and end-of-life (Prod.+EOL.), fuel consumption, and maintenance in three scenarios.

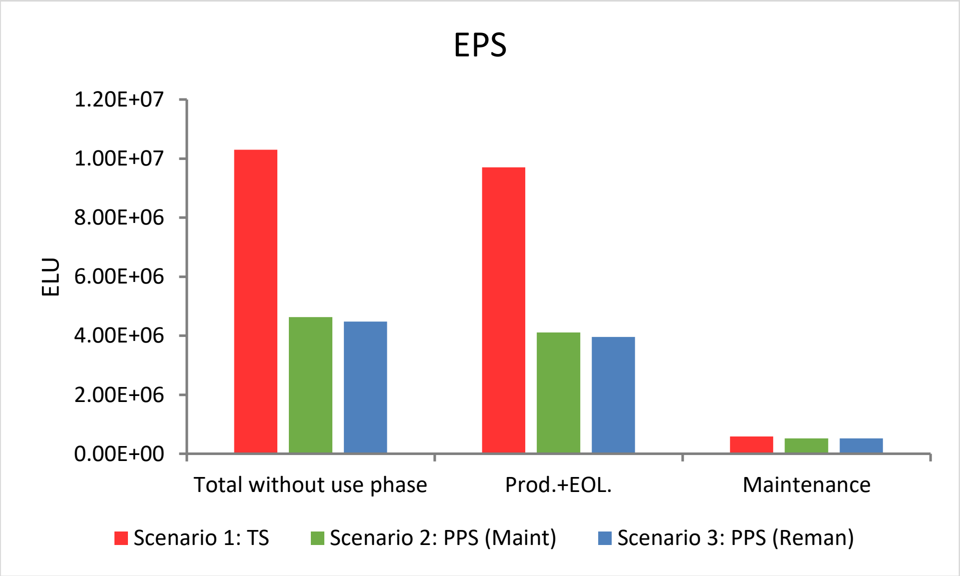

Figure 6. EPS weighting results in ELU for truck production and end-of-life (Prod.+EOL.), and maintenance in three scenarios.

In summary, the characterization and weighting results show that the environmental performance of the PSS model is better than traditional model’s. Improved maintenance can bring more environmental improvement than engine remanufacturing. Fuel consumption makes up the biggest impact in the truck industry but does not affect the relative results as the environmental impacts of fuel consumption in three scenarios doesn’t vary in the study.

7. Sensitivity analysis

The fundamental purpose of this sensitivity analysis is to explore how parameters and assumptions in the study can influence the results. Break-even analyses have been done to answer the question of under which conditions the PSS model is still less environmentally impacting than the traditional model. Parameters, such as uptime, lifetime, technical intervals in maintenance scheme, eco-driving and fuel consumption, have been included in this analysis. All the analyses above are based on the EPS weighting method, but also the sensitivity to other weighting methods is investigated by applying ReCiPe weighting as well.

7.1 Sensitivity analysis for uptime change

In order to show how sensitive the final result is to uptime, a sensitivity analysis has been implemented in three scenarios. The uptime in scenario 1 was assumed to be 85%, and scenario 2 and 3 is 100% in the result part. It can be a high risk from a business perspective for Volvo to keep 100% uptime for the whole life of the trucks. So 100%, 90% and 85% uptime have been chosen in PSS model in a realistic analysis, and 50% of uptime is also set to explore if a dramatic and unrealistic change in uptime can reverse the results. The lifetime of trucks in the traditional model is typically 10^6 km, whereas the trucks in the PSS model have a lifetime of $2 \cdot 10^6$ km. Fuel consumption is not included in uptime change because the same mileages result in the same environmental impacts on fuel consumption. Moreover, including the fuel consumption phase will decrease the sensitivity of parameters like uptime and lifetime.

Figure 7 shows the results of uptime change from 100% to 50%. As shown in the first group, when uptime is 100%, the environmental improvement of the PSS model can reach almost 55%. The environmental improvement decreases along with the decline of uptime. When uptime drops from 100% to 85%, the environmental improvement from the PSS model decrease from 55% to 47%. An uptime decrease of 15% changes the total environmental improvement by 8%, which shows that the final result is not sensitive to changes in uptime. PSS model has a better environmental performance than the traditional model even though the uptime of trucks in the PSS model decreased to 50%. The PSS model still can gain about 10% environmental improvement even when only 50% of uptime is achieved in the PSS model. A 35% of uptime decrease from 85% to 50% lead to a 37% decline in environmental improvement (from 47% to 10%). Therefore, the lower uptime is in the system, the more the sensitive final result will be affected. But still, 50% of uptime is an unrealistic assumption, and 85% of uptime is the acceptable number in use phase from customers’ perspective.

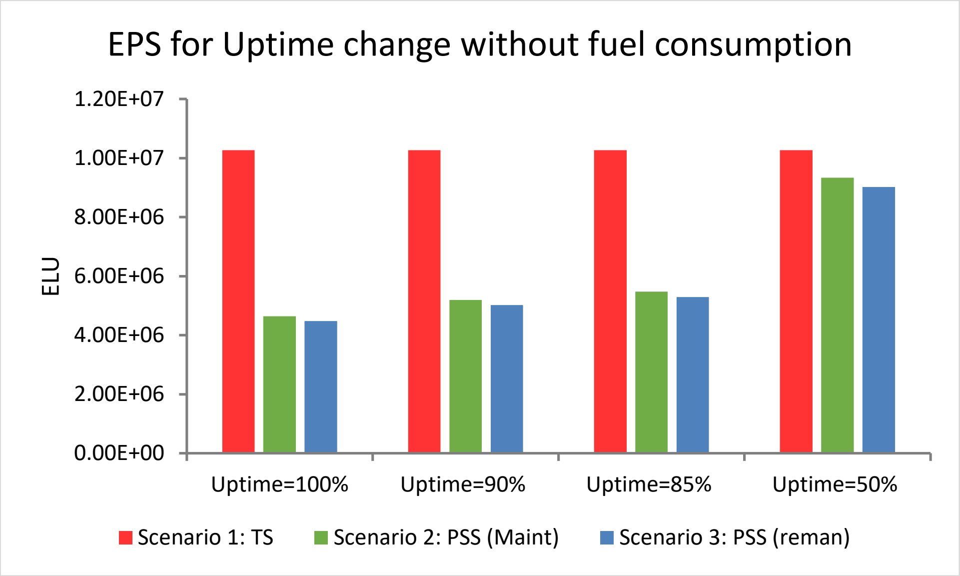

Figure 7. EPS weighting results from different uptime without fuel consumption, 100%, 90%, 85% and 50%.

7.2 Sensitivity analysis for lifetime change

Sensitivity analysis on lifetime change represents different outcomes. While keeping the uptime unchanged in scenario 1, 2 and 3, the lifetime of trucks in the PSS model is changed from $2 \cdot 10^6$ km, to $1.5 \cdot 10^6$ km, $1 \cdot 10^6$ km, and $5 \cdot 10^5$km. An example of the reason why the lifetime would not reach $2 \cdot 10^6$ km is because Volvo is a premium brand, customers are used to enjoying better products and prefer new trucks, which may lead to an unpopular leasing in old trucks, and cause scrapping the trucks before their end-of-life. As well, harsh driving may also lead to a lower lifetime. The figure 8 shows how the sensitive lifetime can change the final result. When the lifetime changes from $2 \cdot 10^6$ km to $5 \cdot 10^5$ km, the environmental improvement in PSS model changes from 55% to around 30% (Scenario 3) to 35% (Scenario 2) more environmental impacts. The third bar groups indicate that even if the lifetime remains constant at $1 \cdot 10^6$ km, PSS model can still have environmental improvements. It also shows the lifetime changes have a significant influence on EPS weighting results, and hence it is a key parameter in affecting the environmental impacts.

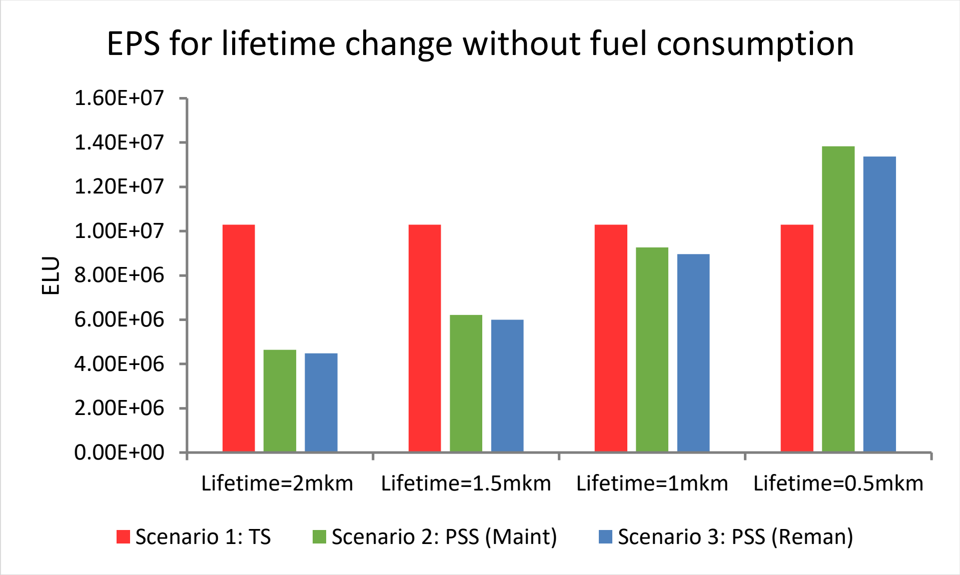

Figure 8. EPS weighting results from different lifetime without fuel consumption, 2 ·10^6 km, 1.5 ·10^6 km, 1 ·10^6 km and 5 ·10^5km.

Another analysis has been performed in figure 9. When the lifetime of FH truck is maintained at around 9 ·10^5 km, the environmental impacts from three scenarios do not vary significantly. It shows if Volvo keeps the FH truck lifetime over 9 ·10^5 km, the PSS model will still have a lower environmental impact than the traditional model.

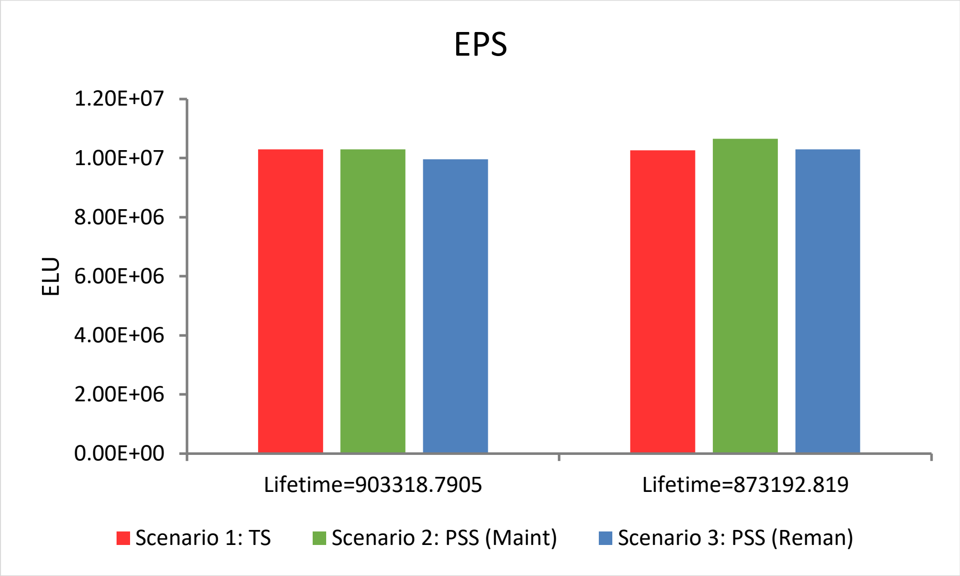

Figure 9. EPS weighting results from lifetime change and even environmental impact in three scenarios. Uptime in scenario 1 is 85%; uptime in scenario 2 and 3 is 100%.

7.3 Sensitivity analysis for simultaneous lifetime and uptime change

When the lifetime cannot reach $2 \cdot 10^6$ km in PSS model but instead remains the same as the traditional scenario ($1 \cdot 10^6$ km), the minimum threshold of uptime change is needed for Volvo to retain lower environmental impacts in the PSS model. A simultaneous sensitivity analysis (figure 10) has been made to find the uptime value under the circumstances above. Consequently, the PSS model will still be less environmentally impacting than the traditional scenario if the uptime in the fleet can reach about 90%.

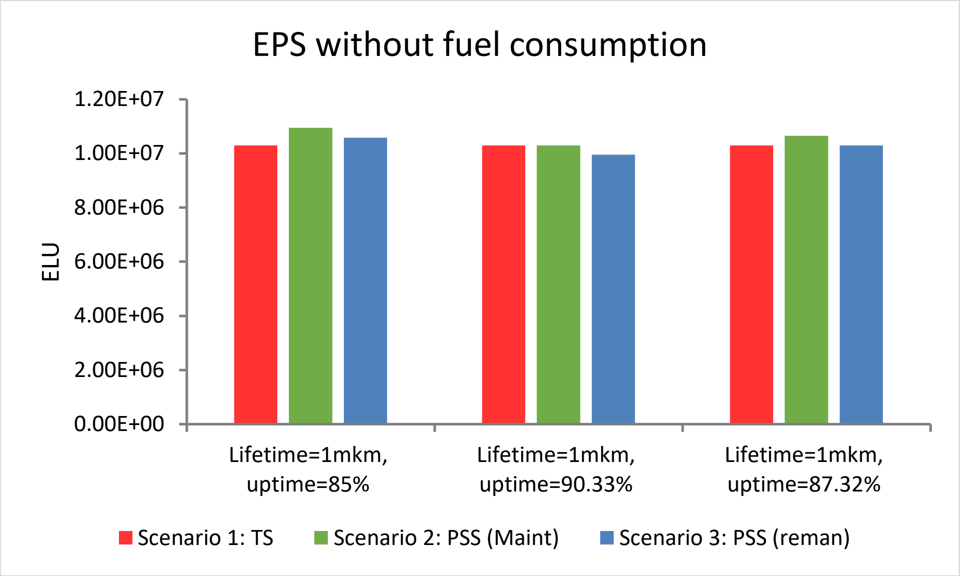

Figure 10. EPS weighting results from uptime change and even environmental impact in three scenarios. Lifetime in scenario 1,2 and 3 remain the same as $1 \cdot 10^6$ km.

7.4 Sensitivity analysis for technical intervals in maintenance scheme

According to the interviews, it has been thought as a tendency that predictive maintenance will replace the corrective and preventive maintenance in the maintenance scheme. Volvo are taking an interest in the environmental impact changes from predictive maintenance. When predictive maintenance replaces the existing maintenance scheme, the technical intervals in each maintenance process can be extended. Assuming the technical intervals in maintenance decrease by 10%, 20% and 30%, the results have been shown in figure 11 below.

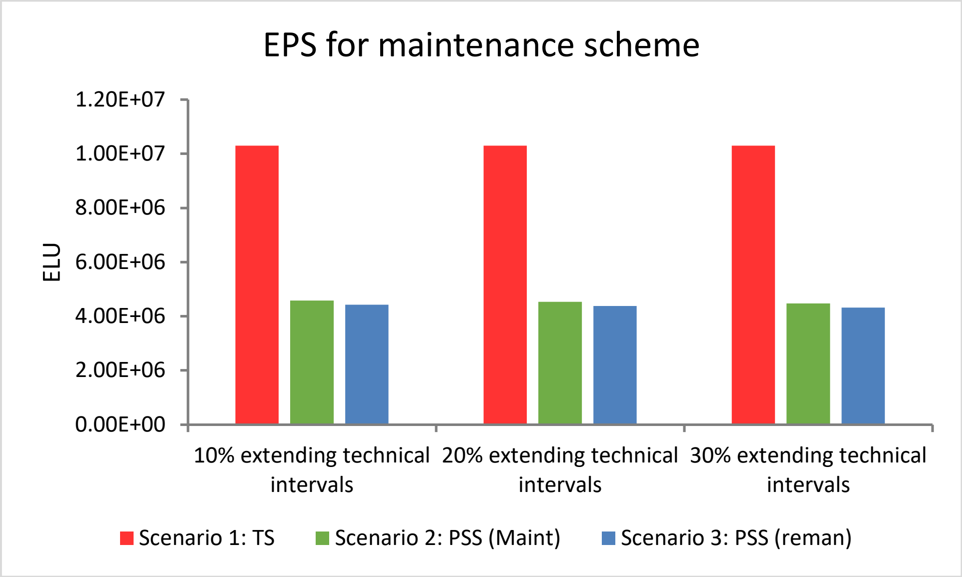

Figure 11. EPS weighting results for total environmental impacts from different technical intervals in maintenance scheme.

As can be seen in figure 11, three groups of the extended technical intervals (from 10% to 30%) describe a close to 1% environmental impact change. This is because of the proportion of maintenance scheme in EPS weighting method occupies a small percentage of total environmental impacts. The technical intervals' changes in maintenance scheme are insufficient to change the final impacts.

7.5 Sensitivity analysis for fuel consumption

In the result part and sensitivity analysis for uptime and lifetime, it assumes three scenarios share the same amount of fuel consumption. When Volvo switches the business model from traditional to PSS, Volvo can guide their customers to eco-driving, which can possibly reduce fuel use by 5% (Volvo Group, n.d). A sensitivity analysis has been studied when the fuel reduction can reach 5%, 10%, and even 30% when the PSS model has been implemented. When the fuel reduction reaches 30% in PSS model, Volvo can gain 18% of environmental improvements other than the improvements from materials.

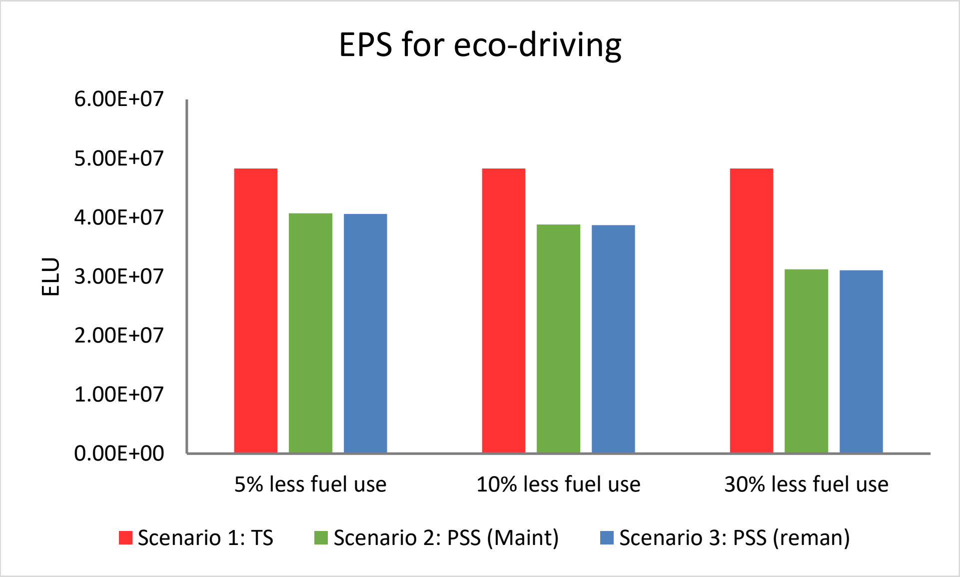

Figure 12. EPS weighting results for eco-driving.

Fuel efficiency improvement is another parameter that will change the final result. According to the existing LCA study, the fuel consumption of Volvo trucks in 2009 was 0.275 l/km. The optimal annual fuel technology improvement is 1%, however, 0.5% is a more realistic number (Transport & Environment, 2015). In this sensitivity analysis, three parameters have been included, i.e., uptime of 100% to 85%, the lifetime of $2 \cdot 10^6$ km to $1 \cdot 10^6$km and fuel consumption by 1% and 0.5% of fuel technology improvement. Eco-driving with 5% of possible fuel reduction is also contained in the fuel efficiency parameter. The relationship between parameters have been shown in the table below (table 14). The parameters in scenario 1 remain unchanged. In scenario 2 and 3, combinations of uptime and lifetime classify the PSS model into four kinds, and the fuel technology improvement and eco-driving segment four kinds of PSS model into two groups.

Table 14. The parameters change (Fuel technology improvement, eco-driving, lifetime and uptime) in product-services-system model.

	PSS 1	PSS 2	PSS 3	PSS 4	PSS 1	PSS 2	PSS 3	PSS 4
Fuel tech.	1%				0.5%			
Eco-driving	5%				5%			
Lifetime (km)	$2 \cdot 10^6$	$2 \cdot 10^6$	$1 \cdot 10^6$	$1 \cdot 10^6$	$2 \cdot 10^6$	$2 \cdot 10^6$	$1 \cdot 10^6$	$1 \cdot 10^6$
Uptime	100%	85%	100%	85%	100%	85%	100%	85%

The lifetime in traditional model is $1 \cdot 10^6$ km or 10 years in year-based measurement but $2 \cdot 10^6$ km (20 years) in PSS model. In order to compare two scenarios with identical standards, it is needed to assume the fleet will have 20 years' experience and starts in the year of 2016.

In scenario 1, because the lifetime of the trucks is 10 years, the fleet undergo two-shift rotation in 20 years. To simplify the model, the fuel use in the first ten years was calculated as the fuel consumption in 2016 and the following ten years used the fuel consumption in 2026. In scenario 2, the fuel consumption in 2016 has been calculated over the whole 20 years. The fuel consumption in 2016 is 0.256l/km and 0.228l/km in 2026 when the annual fuel technology improvement is 1%. The numbers change to 0.265l/km in 2016 and 0.252l/km in 2026 when fuel technology improvement is 0.5%.

Today, the fuel consumption in a remanufactured engine cannot achieve the efficiency of the latest technology, so the fuel consumption for the remanufacturing scenario retains the fuel use in the old period. The numbers chosen for remanufactured engines are 0.32 l/km and 0.285 l/km, which is the fuel consumption in the year of 1996 and 2006 related to the lifetime of $2 \cdot 10^6$ km and $1 \cdot 10^6$ km

Figure 13 describes the comparison of environmental impacts between scenario 1 and 2. The analysis has been done for the EPS weighting method. As can be seen in figure 13, whatever the parameters change, the total environmental impact from maintenance scenario of PSS model will still be lower than the environmental impact of the traditional model. When comparing the green bars and blue bars, it also illustrates the same conclusion in the result part that lifetime change can be more sensitive than uptime change to the result of this study. Besides, higher fuel technology improvement (1%) can decrease by up to 5% of environmental impact when compared to the lower fuel technology improvement (0.5%).

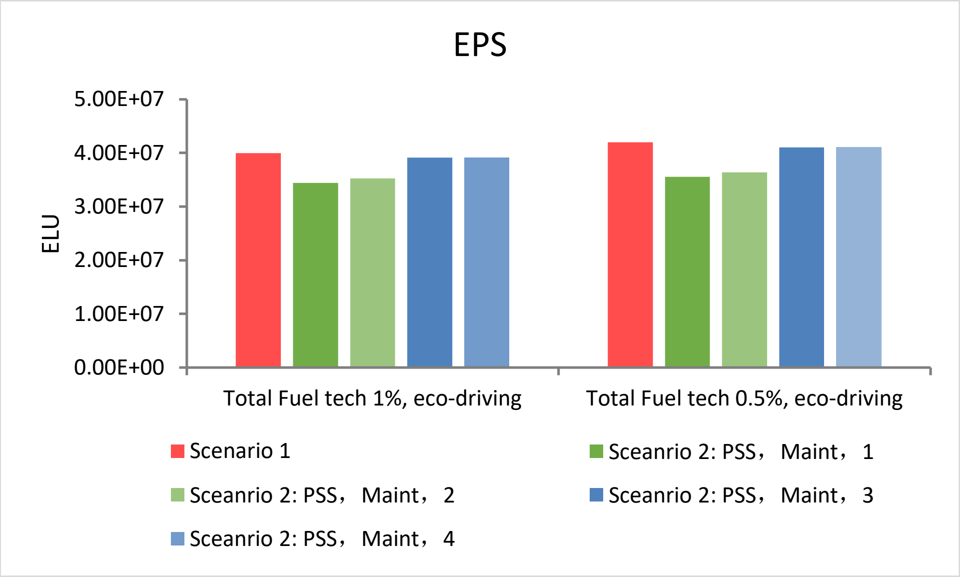

Figure 13. EPS weighting results for the comparison between scenario 1 and 2.

Figure 14 shows the comparison of the environmental impact between scenario 1 and 3. The bars keep near the same level in the figure. Due to the old fuel technology in engines, the environmental impacts in PSS model are higher than the traditional model. Only when the following conditions are met i.e. the uptime is 100%, lifetime is $2 \cdot 10^6$ km, the annual fuel decreasing rate is 0.5%, and the inclusion of eco-driving, can the remanufacturing scenario have less environmental impact than traditional scenario. The highest impact comes from the conditions of 85% uptime, the $2 \cdot 10^6$ lifetime with 1% of the annual fuel decreasing rate and eco-driving. In this case, a PSS model for remanufacturing scenario has 6.5% more environmental impact than the traditional model.

In the remanufacturing scenario, the higher the annual fuel decreasing rate is, and the longer the lifetime of the truck is, the bigger the environmental impact the fleet will gain. In order to achieve a lower environmental impact, the remanufacturing scenario needs to be satisfied to shorten trucks lifetime in the circumstance of low annual fuel decreasing rate.

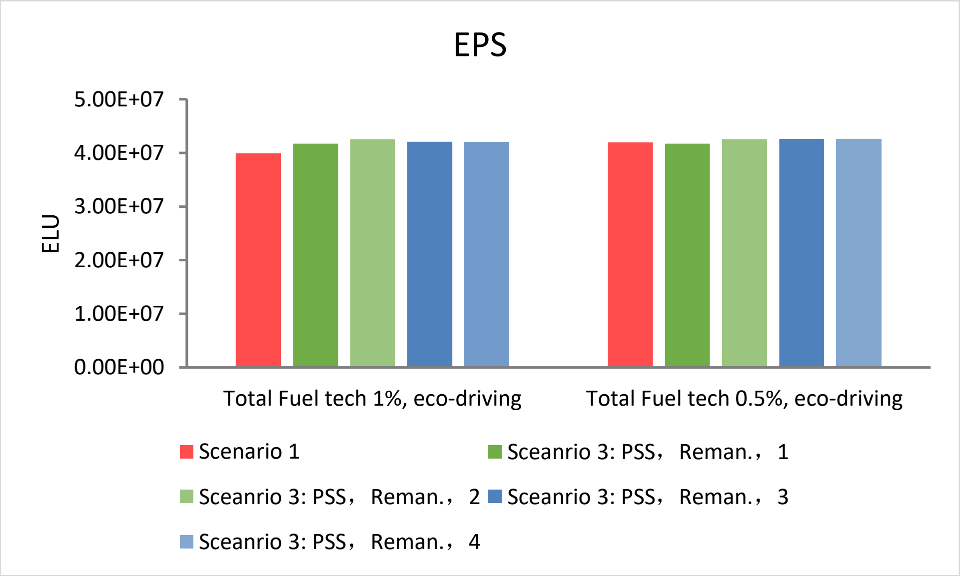

Figure 14. EPS weighting results for the comparison between scenario 1 and 3.

7.6 Sensitivity analysis for ReCiPe weighting method

The ReCiPe weighting method shows a different result compared to the EPS weighting method. As can be seen in figure 15, when considering the fuel consumption, PSS model can save around 1% more of the total impact than the traditional model. The ReCiPe weighting method weights the result under Hierarchist perspective. The weighting factors in ReCiPe are different from those in EPS weighting system, and because of the high weighting factor of crude oil, the diesel combustion dominates almost the entire weighting system in ReCiPe. That is the reason why the bars in fuel consumption contributes to around 95% of total environmental impacts, and the impacts from other processes are drowned in comparison

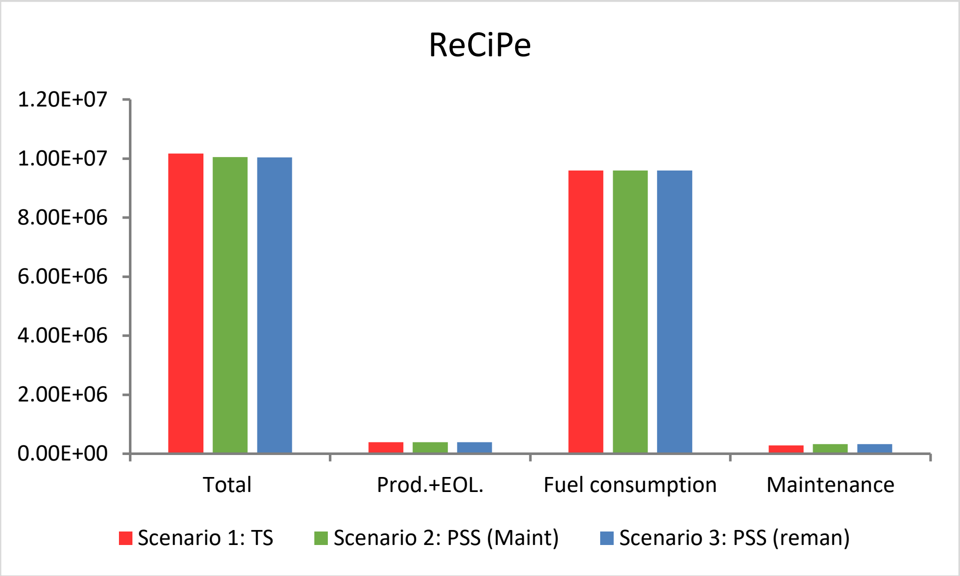

Figure 15. ReCiPe weighting results for truck production and end-of-life (Prod.+EOL.), maintenance, and fuel consumption in three scenarios.

Without considering fuel consumption (see figure 16), PSS model shows an environmental improvement which is 20% greater than the traditional model. The number is smaller than that in EPS weighting system (around 55%). Figure 16 describes the ReCiPe weighting results for truck production, maintenance, and end-of-life phase. It shows truck production and end-of-life phase have almost the same environmental impacts with maintenance phase in scenario 1. In scenario 2 and 3, maintenance phase occupies almost 75% of total impacts. The high impacts in maintenance phase is due to the natural rubber accounting in ReCiPe weighting system. The natural rubber used in tires as exchanging components occupies around 85% of environmental impacts in the maintenance phase. That is the dominant difference between those two weighting systems and the main result change between EPS and ReCiPe results trend

When considering parameters changes e.g. lifetime, uptime and fuel consumption in ReCiPe weighting method, the results are still entirely different when compared with EPS weighting method. Figure 17 shows the ReCiPe results in changes with lifetime, uptime and fuel consumption changes among three scenarios. It shows when including fuel consumption into ReCiPe calculation, the environmental impacts in PSS model represent a higher result than the traditional model. Higher diesel impacts weighted in ReCiPe weighting method lead to more sensitive results if fuel consumption changes.

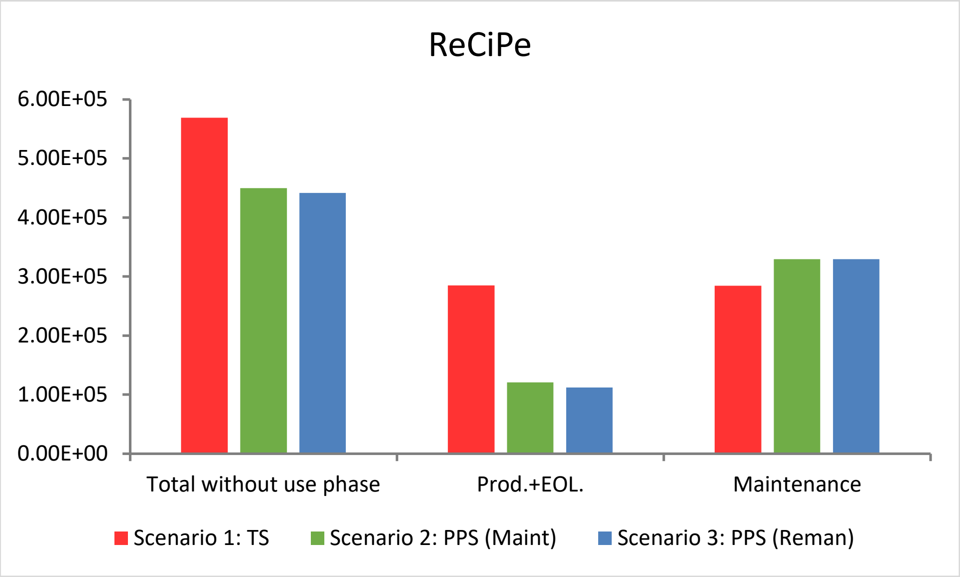

Figure 16. ReCiPe weighting results for truck production and end-of-life (Prod.+EOL.), and maintenance, in three scenarios.

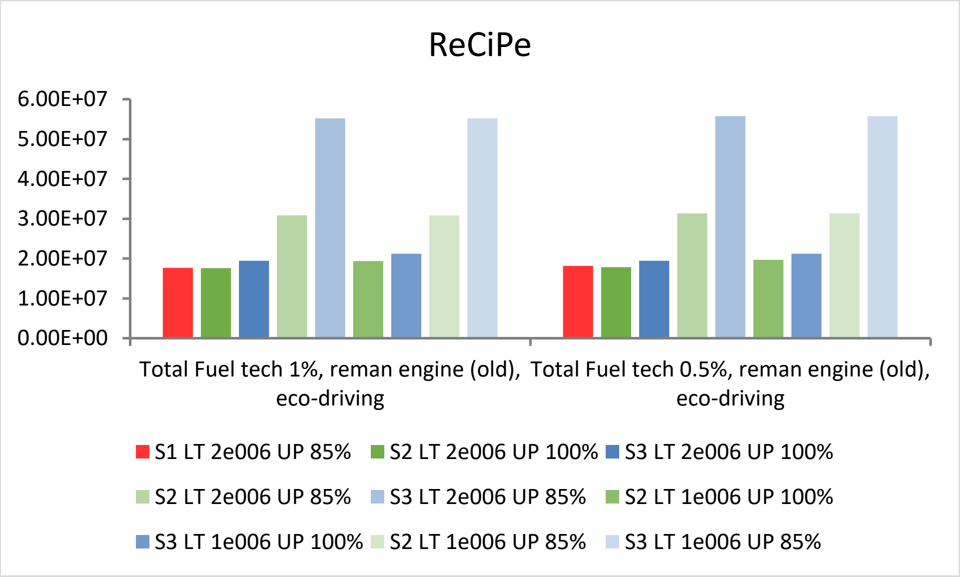

Figure 17. ReCiPe weighting results for parameters change e.g. lifetime (LF), uptime (UT) and fuel consumption in three scenarios: Scenario 1 (S1); Scenario 2 (S2); Scenario 3 (S3).

8. Discussion

This chapter first presents the meaning of the results in this study. Then, it is followed by the discussions of assumptions and methodologies selection that have been made for the delimitation of the study.

8.1 Meaning of the results

As the results show, fuel consumption contributes to a significant part of the total environmental impact. It is an activity that must be considered, in order to develop a solution to sustainable transportation in the truck manufacturing industry today. In order to improve the sustainability of the trucking industry, any means to increase fuel efficiency should be integrated in the design of a PSS model. Fuel advice and services aiming at fuel saving should definitely be integrated in the PSS model for customers.

Services considered in this study, i.e. maintenance and engine remanufacturing, are supposed to decrease the environmental impacts in other activities apart from fuel consumption through a change in fleet size as a result of improvement of uptime and lifetime in PSS model.

However, there is a risk that fuel consumption will increase in the use phase in PSS business, due to a delayed introduction of more fuel-efficient technologies in comparison with in traditional sales. The total lifecycle impacts of trucks in PSS model are determined by uptime, lifetime and fuel efficiency. It is shown that the higher the uptime, or the shorter the lifetime, or the slower the progress in fuel technologies, the better the environmental performance will be. This applies in the case of fuel consumption, as it is a major activity liable for environmental disadvantage. The sensitivity analysis shows that a PSS model with better maintenance services in general could be more environmentally advantageous than traditional sales if changes in lifetime, uptime and fuel efficiency happen in a sensible range that Volvo Trucks is able to approach for trucks. However, adding engine remanufacturing that causes more fuel consumption has completely reversed the environmental advantages of PSS model that maintenance brings.

In reality, truck manufacturing companies has prepared for a shift of product development from diesel trucks to a variety of green trucks, such as biofuel driven and electric trucks etc. In order to cope with serious challenges facing automotive industry, i.e. oil depletion and climate change, green trucks are supposed to scale up to replace fossil trucks in the future. This will lead to a great decline in truck’s environmental impacts caused by fuel consumption. In that case, a shift of concerns will take place from fuel consumption to other activities. From a future-oriented perspective, maintenance is supposed to result in increases in uptime and lifetime in a business transition from traditional sales to PSS model, which in turn would lead to a reduction in the total impacts. With engine remanufacturing, materials consumption is also going to be reduced. In a case of extended lifetime and improved uptime, PSS model is likely to be more environmentally advantageous than traditional sales due to a change in fleet size determined by lifetime and uptime. In the best case, maintenance contributes to a reduction of the impacts of PSS model by approximately 55% compared to traditional sales and engine remanufacturing contributes to a further decrease by 1.5% in addition to maintenance.

The results show the potential environmental improvements of the changes related to only maintenance and remanufacturing in a PSS business. The changes of them are perceived likely to happen if the PSS business is implemented in the future. In a PSS system, Volvo Trucks no longer ends their responsibility for their products after transaction, but becomes responsible over the entire lifespan of the trucks as a result of a change in trucks ownership. This allows Volvo Trucks to have more interactions with trucks and to provide improved maintenance services for the fulfillment of their customers' needs for truck performance. Through the improved maintenance, a truck is expected to increase its use life to the designed lifetime and to raise the uptime to approximately 100% with the adoption of predictive maintenance. The results from the maintenance scenario outlines the environmental potential from the improvement of the maintenance services in the PSS business. In addition, the change in ownership enables the rise of the reverse logistics that Volvo Trucks is currently approaching through the exchange program. Remanufacturing is supposed to go through a great development in the PSS business. Not only increasingly diverse components and parts are about to be remanufactured, but also the scale of the remanufacturing of each component or each part are supposed to expand in the PSS business. However, this study considers only remanufacturing related to one component, the engine. The environmental improvements shown by the results of the remanufacturing scenario are therefore likely to be much smaller than the overall impacts of a full expansion of the remanufacturing of diverse components. Notably, this study does not demonstrate the full environmental improvements of PSS, but only two activities, maintenance and remanufacturing, resulted from the implementation of a PSS business. Some improvement with potential environment consequences are not assessed, such as accelerated innovation and progressive product development and design gained by engaging customers to share their ideas, their experience of Volvo trucks and providing feedback in the PSS business. However, this is no way to conclude whether the environmental impacts resulted from these activities are positive or negative as it is dependent on trade-offs in the product development process between environmental advantages, customer preferences and corporate profits.

8.2 Methodological choices

8.2.1 Different weighting methods: EPS and ReCiPe

Different results are generated when different weighting methods are employed. The global environmental challenges confronting humans are not only energy related impacts but also materials consumption and emissions that mostly concerns in automotive industry. On the contrary to EPS which has a more balanced view on energy resources and materials, ReCiPe gives fairly high factors for energy resources (especially crude oil) and low factors for materials compared with EPS. ReCiPe results show fuel consumption account for a larger share of environmental impacts to the total and a change in fleet size has a lower contribution to environmental advantage of PSS model compared with EPS results. When measured by ReCiPe, the results indicate an opposite trend for PSS business model when maintenance is considered since environmental improvements gained from a shrunken fleet size cannot offset increased negative environmental impacts from fuel consumption as a result of delayed introduction of fuel efficient technologies along with lifetime extension of trucks. A PSS model would therefore have worse environmental performance when engine remanufacturing is added. The PSS business model is likely to be more environmentally disadvantageous than traditional sales considering fuel consumption in the case of both maintenance and engine remanufacturing. When fuel consumption is excluded, ReCiPe depicts the similar patterns of PSS model for potential environmental improvements. Both maintenance and engine remanufacturing could have brought forth environmental improvements for PSS model despite lowered improvements from the change in fleet size.

This illustrates comparisons of environmental performances between traditional sales and PSS model when energy issues are particularly taken into concern. It tells the effects on environmental consequence of shift in business model in an extreme case that the main focus is placed on energy instead of a balance of materials and energy.

8.3 Assumption selection

8.3.1 Lifetime

Changes in lifetime for trucks are examined in sensitivity analysis only concerning PSS model, not traditional sales. It is perceived to be uncertain that 1 million kilometers as a lifetime for trucks was given by the previous LCA study. It should have been investigated in sensitivity analysis to understand the possible effects on the results along with changes in lifetime in the existing business apart from changes in PSS business. In the case of two variables to be investigated in sensitivity analysis, it is appropriate to only look at the changes in a relative sense rather than focusing on the absolute values of the truck lifetime for both business models. Critically, it is the investigation of a relative value in traditional sales to the one in PSS model that indicates the possible change along with the move from traditional sales to PSS business. In this regard, a lack of examination in lifetime under traditional sales does not have any effect on the results as the relative values as for the lifetime in traditional sales model to the one in PSS model have been indicated in the sensitivity analysis when changes in lifetime under PSS are explored.

8.3.2 Maintenance

Data available regarding maintenance are only a standardized 5-year maintenance scheme which reveals only regular replacement of parts based on annual services. Energy consumption for maintenance and transport are not included. The environmental impacts indicated for three scenarios in this study are therefore lower than their actual impacts. In addition, the environmental impacts of maintenance are assessed based on an assumption that all components are functioning within its designed maintenance intervals and no other replacement of parts and components is needed. However, in reality, it is the case that many more parts and components need to be replaced during the use phase. The environmental assessments of the maintenance phase for three scenarios are underestimated. Nevertheless, in the PSS business, trucks are equipped with better maintenance services. Less replacement of parts and components is supposed to be required than it is in traditional sales. Thus, a transition from traditional sales to PSS business is expected to bring forth even larger environmental improvements than the results shown. Moreover, the weighting method choice will also influence the final results. The maintenance results from ReCiPe weighting method occupy more percentage of total environmental impacts than EPS weighting method due to the high weighting of natural rubber in ReCiPe weighting system. Predictive maintenance seems to be a future solution to replace present preventive and corrective maintenance. With more monitoring sensors used in trucks, Volvo can easily prepare the right time for truck maintenance. This new type of maintenance is predicted to increase trucks lifetime and uptime and decrease the maintenance frequencies in the trucks' whole life, which will also have a positive environmental impact in the maintenance phase.

8.3.3 Remanufacturing

Considering the difficulties in data collection for remanufacturing within a limited time frame, this study focuses only on the remanufacturing of engines rather than components that have been remanufactured in practice and are expected to be remanufactured in the future. As a result, the environmental impacts of the study do not demonstrate the full potential of remanufacturing in PSS business. In the future, the environmental performance of remanufacturing for Volvo Trucks would no doubt be better than what our study shows since more components will be remanufactured. But it is uncertain whether the PSS business concerning remanufacturing of more components has a better performance than traditional sales or not, as it is shown that the PSS scenario with engine remanufacturing tends to be environmentally disadvantageous if fuel consumption and improvement of engine technologies are considered. It is unknown whether the remanufacturing of more components can offset the negative impacts resulted from engine remanufacturing on fuel consumption or not.

As scenario two shows, PSS without engine remanufacturing has a better environmental performance. If other components instead of engines are remanufactured, as is the case in PSS with remanufacturing, the fuel consumption remains the same as in scenario 2, and the amount of materials consumed are less than they are in scenario 2. The environmental performance of PSS with remanufacturing is, in this case, better than in scenario 2. That is, PSS with remanufacturing are supposed to have a better performance than PSS without remanufacturing if other components, not engines are remanufactured in PSS business. This, however, is true based on an assumption that the improvement of fuel efficiency is only a result of engine technologies progress. It contradicts the fact that fuel efficiency has improved along with not only the progress in engine technologies but also in other components, such as drivetrain, tires and so on. So it is unknown whether removing only the engine from the remanufacturing list but adding more other components in PSS contributes to a better performance in environmental dimension or not compared with scenario 2. It needs a complete assessment of remanufacturing with more components. But it is sure to say, PSS with remanufacturing other components than the ones relevant for fuel consumption are more environmentally advantageous than PSS without remanufacturing.

If fuel consumption is excluded from the assessment, considering the shift of business from diesel trucks to electric trucks in the future, the uncertainties are then removed, and PSS with remanufacturing contributes to lowering environmental impacts. The more components are recycled; the more environmental improvements are gained. PSS has higher environmental potentials than traditional sales from the material efficiency perspective.

8.3.4 End of life

Only rubber and metals are modeled at the end of life phase with recycling, and all the other materials are not taken into consideration. No investigation is made as to how the other materials have been treated and what it would be like in PSS business. The impacts in the end of life phase are underestimated for three scenarios, but the underestimation is likely not to refute the results of the comparison of three scenarios. This is because no differences in end of life phase are perceived to happen between traditional sales and PSS in regards to incineration and to the landfill of other materials that are not under control of Volvo trucks.

8.3.5 Product development

The changes in product design are not explored and assessed in this study, but these are likely to take place in PSS business. In future PSS business, Volvo Trucks will have more information on the use of trucks through interactions with customers and trucks as responsibility will no longer end after the transaction, but last for the full lifetime of trucks. This will potentially lead to accelerated innovations and progressive product development. However, it does not mean these are surely environmentally benign. The environmental performance of the innovative products is dependent on tradeoffs in terms of design between environmental advantage, customer preference, and corporate profits.

8.3.6 Consumption patterns

It is assumed in the configuration of the fleet for PSS business that no changes in consumption patterns happen in the shift from truck sales to PSS. However, some changes are perceived to likely happen. For instance, high demand for new trucks appears in current leasing market as opposed to the low demand for aged trucks. If it is the case in future PSS business, trucks would be expected to retire before approaching its designed lifetime, even shorter than its actual lifetime which is ten years currently. The demand for new trucks to fulfill needs are supposed to be on the increase, and aged trucks are going to stand still. As shown in the sensitivity analysis, lifetime is sensitive to the total environmental impacts. The environmental performance of PSS is perceived to be disastrous due to a waste of a significant amount of transport capacity. This, however, remains uncertain due to the ambiguous comprehension of the likely changes in consumption patterns that has not occurred. Besides, PSS seems to give rise to restraining personalization in trucks. No sense of belonging may keep the drivers away from Volvo PSS model. PSS model still needs to be tested in a real business condition, and the environmental impact result can be more valuable.

9. Conclusions

PSS would definitely be a better choice for Volvo Trucks from a long-term environmental sustainability point of view as resource scarcity is considered a major problem facing truck manufacturing companies in the future, in the case that the reliance on fossil fuels is solved and green trucks, e.g. electric trucks are scaled to replace fossil trucks. In general, improved maintenance has a large potential to reduce the negative environmental impacts of the business. It contributes to an improvement in environmental performance by approximately 55% compared with the scenario of traditional sales in terms of the total lifecycle impacts (excluding fuel consumption) measured by EPS. This is primarily due to a decline in the number of trucks demanded for the fulfillment of customers' needs as a result of the extension of trucks' lifetime to twice as long as their original one through better maintenance provision. Without considering the fuel consumption, engine remanufacturing makes a contribution to the environmental advantage of the PSS business, but only makes a contribution to further environmental improvement by 1.5% in the PSS business compared with the maintenance scenario as the results reveal. Remanufacturing has far lower contribution to environmental improvements of the PSS business than maintenance since only engine D13, which accounts for a small proportion (about 5%) of the total impacts in the existing business, are considered to be remanufactured in this study.

However, it remains uncertain in terms of the advantages of PSS from a short-term environmental sustainability perspective, when considering improvements of fuel efficiency, by 0.5% and 1% based on EPS weighting. Maintenance still has positive contribution to environmental improvement in the PSS business. Nevertheless, if fuel efficiency improvements are takin into account, engine remanufacturing has negative contribution to the environmental performance of PSS business and subdues the environmental improvements gained from maintenance. It is because engine remanufacturing delays the introduction of more fuel-efficient technologies.

In addition, a disparity is indicated regarding the environmental potential of maintenance in the PSS business when the ReCiPe weighting method is employed instead of EPS. Maintenance in the ReCiPe result has a negative contribution to the environmental performance of the PSS business because it gives a higher weighting factor to energy resources. And the negative result in engine remanufacturing has further been magnified in ReCiPe weighting method.

10. Recommendations

PSS is a business model that is not by default environmentally advantageous as is shown in this LCA study. The plan of PSS, i.e. what engineering activities to include in a PSS business, are key to its environmental outcome. To facilitate the transition of Volvo Trucks toward sustainable industrial practice, the key is to ensure the extension of trucks' lifetime and maintenance is thus recommended to be implemented for PSS model. Moreover, engine remanufacturing is not recommended for trucks or other applications with a high use-phase impact that gets better from year to year as a consequence of technological progress. A PSS in such a case should focus on material recycling rather than remanufacturing. It can still be beneficial to remanufacture many other components that do not affect the fuel consumption as much as engines. Remanufacturing of engines would be recommended only if it could be realized that fuel efficient technologies are able to be introduced in the process of engines remanufacturing through the redesign and modularization.

If fuel consumption is no longer a concern in the future, both maintenance and remanufacturing activities (including engine remanufacturing) enable PSS business to have a better environmental performance.

10.1 Further studies

To assess the full environmental potentials of PSS, uncertainties related to methodologies selection indicated in the discussion need to be further investigated. Further studies are suggested to explore the likely changes in relation to product development, and consumption patterns and a complete assessment of remanufacturing. In addition, assessment of maintenance and end of life phases could be further improved by carrying out a comprehensive inventory investigation and collecting lacking data. Also, a comprehensive assessment of the economic consequences from switching to a PSS business model needs to be made.

11. References

Allen, R.C. 2006. The British Industrial Revolution in Global Perspective: How Commerce Created the Industrial Revolution and Modern Economic Growth. Available at: https://www.nuffield.ox.ac.uk/users/Allen/unpublished/econinvent-3.pdf. [21 November 2016].

Barquet, A.P. Seidel, J. Seliger, G. and Kohl, H. 2016. Sustainability factors for PSS business models. Procedia CIRP. Vol. 47, pp. 436-441.

Baumann, H and Tillman, A. 2004. The Hitch Hiker's Guide to LCA – An orientation in life cycle assessment methodology and application. Dimograf, Poland.

Beuren, F.H. Gomes Ferreira, M. and Cauchick Miguel, P.A. 2013. Product-service systems: a literature review on integrated products and services. Journal of Cleaner Production. Vol. 47, pp. 222-231.

Chierici, E. and Copani, G. 2016. Remanufacturing with Upgrade PSS for New Sustainable Business Models. Procedia CIRP. Vol. 47, pp. 531-536.

D'Elsa, C.V. 2010. Forward. In: Global Footprint Network, the State of the Art in Ecological Footprint Theory and Applications - Footprint Forum 2010. [PDF] Available at: <http://www.footprintnetwork.org/images/uploads/Academic_Conference_Book_of_Abastracts.pdf> [8 December 2016].

Gaiardelli, P. Resta, B. Martinez, V. Pinto, R. and Albores, P. 2014. A classification model for product-service offerings. Journal of Cleaner Production. Vol. 66, pp. 507-519.

Geum, Y. and Park Y. 2011. Designing the sustainable product-service integration: a product-service blueprint approach. Journal of Cleaner Production. Vol. 19, pp. 1601-1614.

Goedkoop M., Heijungs R, Huijbregts M., De Schryver A.;Struijs J., Van Zelm R. (2013), ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and 39 the endpoint level; First edition Report I: Characterisation, Netherlands: Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer

Joint Research Center – Institute for Environment and Sustainability, 2010. ILCD handbook – Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment. [pdf] Available at: <http://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-LCIA-Background-analysis-online-12March2010.pdf> [5 December 2016].

Lindahl, M. Sundin, E. and Sakao, T. 2014. Environmental and economic improvements of integrated Product Service Offerings quantified with real business cases. Journal of Cleaner Production. Vol. 64, pp. 288-296.

Lindkvist, L. and Sundin, E. 2016. The role of Product-Service Systems regarding information feedback transfer in the product life-cycle including remanufacturing. Procedia CIRP. Vol. 47, pp. 311-316.

Mahut, F. Daaboul, J. Bricogne, M. and Eynard, B. 2015. Survey on Product-Service System applications in the automotive industry. IFAC-PapersOnline. Vol. 48(3), pp. 840-847.

Maxwell, D. Sheate, W. and Vorst, R. 2006. Functional and systems aspects of the sustainable product and service development approach for industry. Journal of Cleaner Production. Vol. 14, pp. 1466-1479.

Pigosso, D.C.A. and McAloone, T.C. 2015. Supporting the development of environmentally sustainable PSS by means of the Ecodesign Maturity Model. Procedia CIRP. Vol. 30, pp. 173-178.

Reim, W. Parida, V. and Örtqvist, D. 2015. Product-Serivce Systems (PSS) business models and tactics – a systematic literature review. Journal of Cleaner Production. Vol. 97, pp. 61-75.

Sousa, T.T., and Cauchick Miguel, P.A. 2015. Product-service systems as a promising approach to sustainability exploring the sustainable aspects of a PSS in Brazil. Procedia CIRP. Vol. 30, pp. 138-143.

Sundin, E. and Bras, B. 2005. Making functional sales environmentally and economically beneficial through product remanufacturing. Journal of Cleaner Production. Vol. 13(9), pp. 913-925.

Transport & Environment, 2015. Lorry CO_2 – why Europe needs standards. [pdf] Available at: https://www.transportenvironment.org/sites/te/files/publications/2015_06_Lorry_co2_briefing_update_US_PHASE_III.pdf> [30 October 2016].

Tukker, A. 2015. Product services for a resource-efficient and circular economy- a review. Journal of Cleaner Production. Vol. 97, pp 76-91.

Williams, A. 2007. Product service systems in the automobile industry: contribution to system innovation? Journal of Cleaner Production. Vol. 15, pp. 1093-1103.

Vezzoli, C. Ceschin, F. Diehl, J.C. and Kohtala, C. 2015. New design challenges to widely implement 'Sustainable Product-Serivce Systems'. Journal of Cleaner Production. Vol. 97, pp. 1-12.

Volvo Group, 2015. The Volvo Group annual and sustainability report. [pdf] Available at: <http://www3.volvo.com/investors/finrep/ar15/ar_2015_eng.pdf> [30 October 2016].

Volvo Group, n.d. Training and advice to save even more fuel. [online] Available at: <http://www.volvotrucks.com/en-en/about-us.html> [30 October 2016].

Volvo Trucks n.d.a. About us. [online] Available at: <http://www.volvotrucks.com/en-en/about-us.html > [30 October 2016].

Volvo Trucks n.d.b. Our trucks. [online]Available at: <http://www.volvotrucks.com/en-en/trucks.html> [30 October 2016].

12. Appendix

Appendix 1: Inventory results and environmental effects in scenario 1

Scenario 1	**Unit**	**Production**	**Maintenance**	**EOL**
Primary renewable energy	MWh	2,46E+03	3,17E+02	9,46E+01
Primary non-renewable	MWh	8,53E+03	2,92E+03	-1,06E+03
Total Primary Energy	MWh	1,10E+04	3,23E+03	-9,69E+02
Materials Production	kg	8,73E+05		
Materials Maintenance	kg		2,95E+05	
Materials End-of-Life	kg			7,31E+05
CO	kg	1,00E+04	6,04E+02	-7,43E+03
CO_2	kg	2,12E+06	4,08E+05	-5,51E+05
VOC (including NMVOC)	kg	6,25E+03	1,22E+03	-1,48E+03
NMVOC	kg	1,28E+03	2,82E+02	-8,42E+01
NOx	kg	3,83E+03	1,33E+03	-8,75E+02
SO_2	kg	1,07E+04	1,19E+03	-3,97E+03
PM Particular Matter	kg	1,68E+03	1,88E+02	-4,18E+02
Use of water excluding cooling	m3	9,34E+05	1,06E+05	-6,45E+04
Use of water, cooling	m3	1,41E+04	2,44E+03	5,57E+03
Total water	m3	9,48E+05	1,08E+05	-5,89E+04
BOD	kg	5,37E+02	1,49E+02	-2,77E+01
COD	kg	1,42E+03	2,89E+02	-2,08E+01
Hazardous waste	kg	2,62E+04	2,11E+02	-5,42E+03
waste	kg	2,84E+05	4,58E+03	-3,83E+04
Total waste	kg	3,10E+05	4,79E+03	-4,38E+04
Carbon footprint	kg CO2-Equiv.	2,23E+06	3,94E+05	-6,10E+05
Environmental footprint (EPS)	ELU	1,67E+07	5,91E+05	-6,96E+06
ReCiPe	(Person equivalents weighted)	3,87E+05	3,53E+05	-1,03E+05
Global Warming Potential (GWP)	kg CO2-Equiv.	2,23E+06	3,94E+05	-6,10E+05
Abiotic depletion Potential (ADP)	kg Sb-Equiv.	4,50E+01	6,64E+00	-1,55E+01
Acidification Potential (AP)	kg SO2-Equiv.	1,53E+04	2,35E+03	-5,30E+03
Human Toxicity Potential (HTP)	CTUh	7,95E-01	6,33E-02	-2,35E-01

Appendix 2: Inventory results and environmental effects in scenario 2

Scenario 2	Unit	Production	Maintenance	EOL
Primary renewable energy	MWh	1,04E+03	3,03E+02	4,01E+01
Primary non-renewable	MWh	3,62E+03	2,72E+03	-4,51E+02
Total Primary Energy	MWh	4,66E+03	3,02E+03	-4,11E+02
Materials Production	kg	3,70E+05		
Materials Maintenance	kg		2,75E+05	
Materials End-of-Life	kg			4,63E+05
CO	kg	4,25E+03	5,67E+02	-3,15E+03
CO2	kg	8,97E+05	3,85E+05	-2,33E+05
VOC (including NMVOC)	kg	2,65E+03	1,15E+03	-6,26E+02
NMVOC	kg	5,41E+02	2,65E+02	-3,57E+01
NOx	kg	1,62E+03	1,25E+03	-3,71E+02
SO2	kg	4,55E+03	1,10E+03	-1,68E+03
PM Particular Matter	kg	7,10E+02	1,77E+02	-1,77E+02
Use of water excluding cooling	m3	3,96E+05	9,92E+04	-2,73E+04
Use of water, cooling	m3	5,98E+03	2,32E+03	2,36E+03
Total water	m3	4,02E+05	1,02E+05	-2,50E+04
BOD	kg	2,27E+02	1,39E+02	-1,17E+01
COD	kg	6,03E+02	2,83E+02	-8,83E+00
Hazardous waste	kg	1,11E+04	2,03E+02	-2,30E+03
waste	kg	1,20E+05	4,09E+03	-1,62E+04
Total waste	kg	1,31E+05	4,29E+03	-1,85E+04
Carbon footprint	kg CO2-Equiv.	9,46E+05	3,72E+05	-2,58E+05
Environmental footprint (EPS)	ELU	7,06E+06	5,22E+05	-2,95E+06
ReCiPe	(Person equivalents weighted)	1,64E+05	3,29E+05	-4,35E+04
Global Warming Potential (GWP)	kg CO2-Equiv.	9,46E+05	3,72E+05	-2,58E+05
Abiotic depletion Potential (ADP)	kg Sb-Equiv.	1,91E+01	5,73E+00	-6,57E+00
Acidification Potential (AP)	kg SO2-Equiv.	6,48E+03	2,18E+03	-2,25E+03
Human Toxicity Potential (HTP)	CTUh	3,37E-01	5,96E-02	-9,96E-02

Appendix 3: Inventory results and environmental effects in scenario 3

Scenario 3	**Unit**	**Production**	**Maintenance**	**EOL**
Primary renewable energy	MWh	9,44E+02	3,03E+02	3,73E+01
Primary non-renewable	MWh	3,58E+03	2,72E+03	-4,39E+02
Total Primary Energy	MWh	4,52E+03	3,02E+03	-4,02E+02
Materials Production	kg	3,38E+05		
Materials Maintenance	kg		2,75E+05	
Materials End-of-Life	kg			4,31E+05
CO	kg	4,04E+03	5,67E+02	-3,03E+03
CO_2	kg	8,71E+05	3,85E+05	-2,26E+05
VOC (including NMVOC)	kg	2,58E+03	1,15E+03	-6,04E+02
NMVOC	kg	5,13E+02	2,65E+02	-3,34E+01
NOx	kg	1,67E+03	1,25E+03	-3,59E+02
SO_2	kg	4,49E+03	1,10E+03	-1,67E+03
PM Particular Matter	kg	6,71E+02	1,77E+02	-1,75E+02
Use of water excluding cooling	m3	2,61E+05	9,92E+04	-2,57E+04
Use of water, cooling	m3	5,92E+03	2,32E+03	2,20E+03
Total water	m3	2,67E+05	1,02E+05	-2,35E+04
BOD	kg	1,95E+02	1,39E+02	-1,04E+01
COD	kg	5,62E+02	2,83E+02	-8,37E+00
Hazardous waste	kg	9,91E+03	2,03E+02	-2,20E+03
waste	kg	9,33E+04	4,09E+03	-1,44E+04
Total waste	kg	1,03E+05	4,29E+03	-1,66E+04
Carbon footprint	kg CO2-Equiv.	9,46E+05	3,72E+05	-2,58E+05
Environmental footprint (EPS)	ELU	7,06E+06	5,22E+05	-2,95E+06
ReCiPe	(Person equivalents weighted)	1,64E+05	3,29E+05	-4,35E+04
Global Warming Potential (GWP)	kg CO2-Equiv.	9,46E+05	3,72E+05	-2,58E+05
Abiotic depletion Potential (ADP)	kg Sb-Equiv.	1,91E+01	5,73E+00	-6,57E+00
Acidification Potential (AP)	kg SO2-Equiv.	6,48E+03	2,18E+03	-2,25E+03
Human Toxicity Potential (HTP)	CTUh	3,37E-01	5,96E-02	-9,96E-02

Appendix 4. Detailed results for impact categories

Table 15. Global Warming Potential in CO_2-euqivalents for truck production, maintenance fuel consumption and end-of-life in three scenarios.

	Scenario 1: TS	Scenario 2: PSS (Maint.)	Scenario 3: PSS (Reman.)
Total	1.03E+08	1.02E+08	1.02E+08
Production	2232440	945949.2	891058.1
Fuel consumption	1.01E+08	1.01E+08	1.01E+08
Maintenance	394450.8	371854.5	371854.5
End-of-life	-609560	-258288	-235252

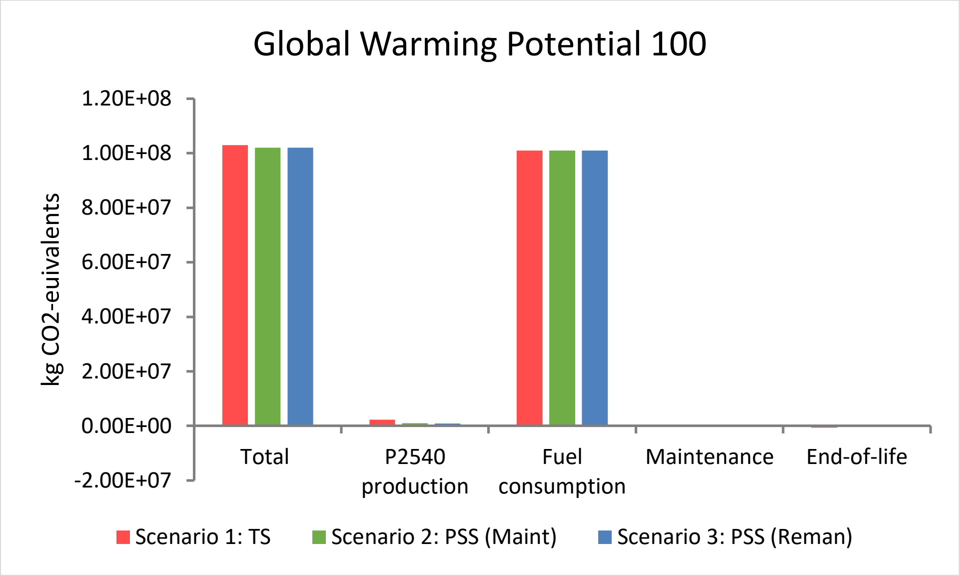

Figure 18. Global Warming Potential in CO_2-euqivalents for truck production, maintenance fuel consumption and end-of-life in three scenarios.

Table 16. Global Warming Potential for CO_2-euqivalents for truck production, maintenance and end-of-life in three scenarios.

	Scenario 1: TS	Scenario 2: PSS (Maint)	Scenario 3: PSS (Reman)
Total without use phase	2017331	1059516	1027661
Material	1926078	816134.5	777838
External transports	40349.79	17097.37	14895.75
Volvo production	266012.8	112717.3	93253.73
Maintenance	394450.8	371854.5	371854.5
EOL	-609560	-258288	-235252

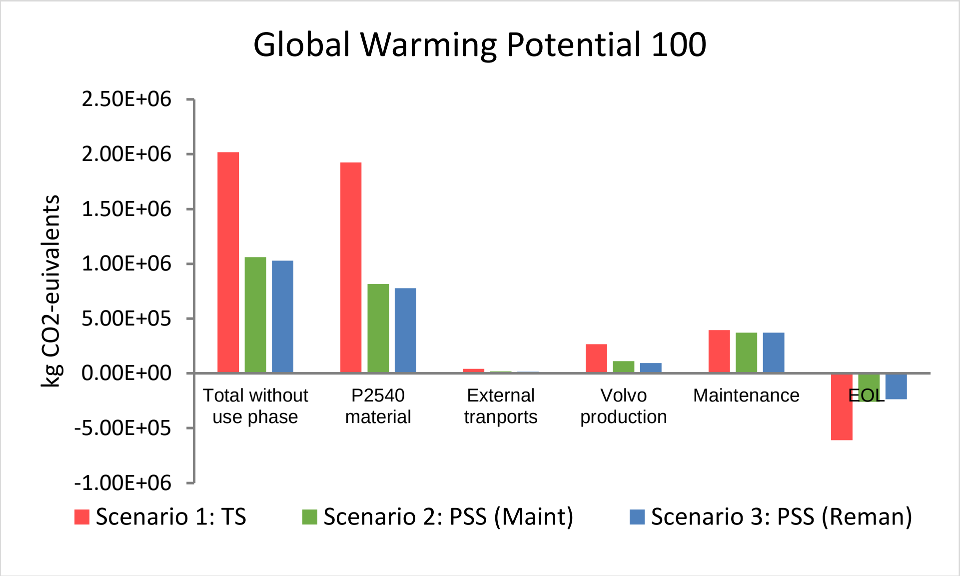

Figure 19. Global Warming Potential for CO_2-euqivalents for truck production, maintenance and end-of-life in three scenarios.

Table 17. Global Warming Potential in CO_2-euqivalents in a fleet maintenance condition.

Maintenance in fleet	**Scenario 1**	**Scenario 2&3**
Total maintenance	394450.8	371854.5
Corrective maintenance	398240	371611.3
Preventive maintenance	27757.66	32158.64
Maintenance EOL	-31546.8	-31915.3

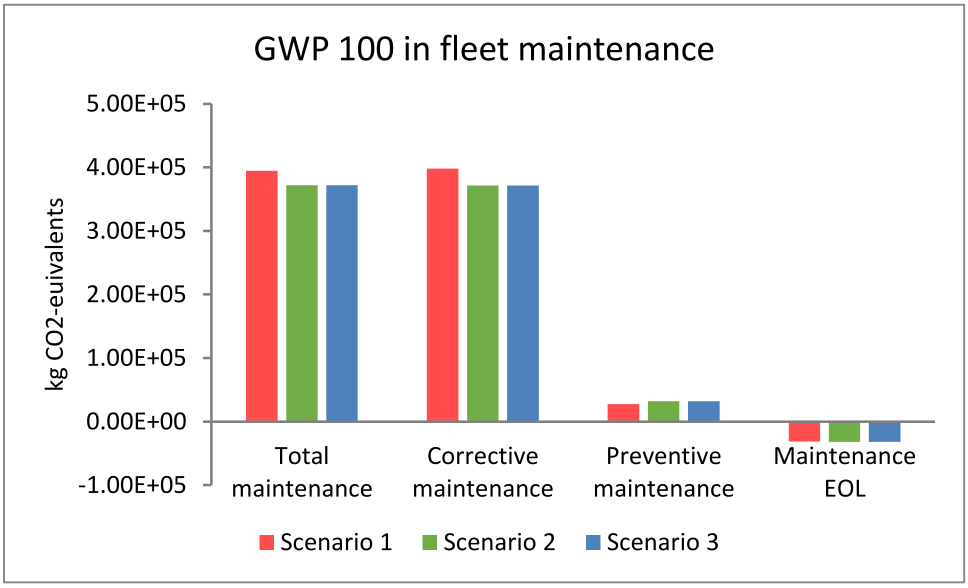

Figure 20. Global Warming Potential in CO_2-euqivalents in a fleet maintenance condition.

Table 18. Abiotic Depletion Potential in Sb-equivalents for truck production, maintenance, fuel consumption and end-of-life in three scenarios.

Comparison between business models	Scenario 1: TS	Scenario 2: PSS (Maint)	Scenario 3: PSS (Reman)
Total	63.90135	45.98054	44.6952
Production	45.01428	19.07385	17.44939
Fuel consumption	27.74567	27.74567	27.74567
Maintenance	6.636752	5.726848	5.726848
EOL	-15.4953	-6.56582	-6.2267

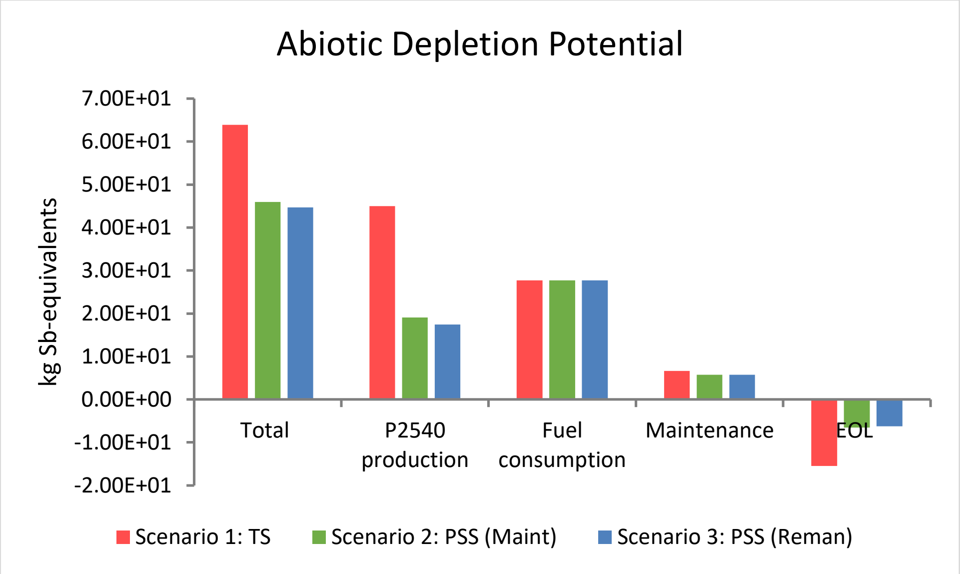

Figure 21. Abiotic Depletion Potential in Sb-equivalents for truck production, maintenance, fuel consumption and end-of-life in three scenarios.

Table 19. Abiotic Depletion Potential in Sb-equivalents for truck production, maintenance and end-of-life in three scenarios.

Comparison between business models	Scenario 1: TS	Scenario 2: PSS (Maint)	Scenario 3: PSS (reman)
Total without use phase	36.15568	18.23487	16.94954
Material	44.78557	18.97694	17.18931
External transports	0.002644	0.00112	0.00112
Volvo production	0.226058	0.095787	0.080127
Maintenance	6.636752	5.726848	5.726848
EOL	-15.4953	-6.56582	-6.2267

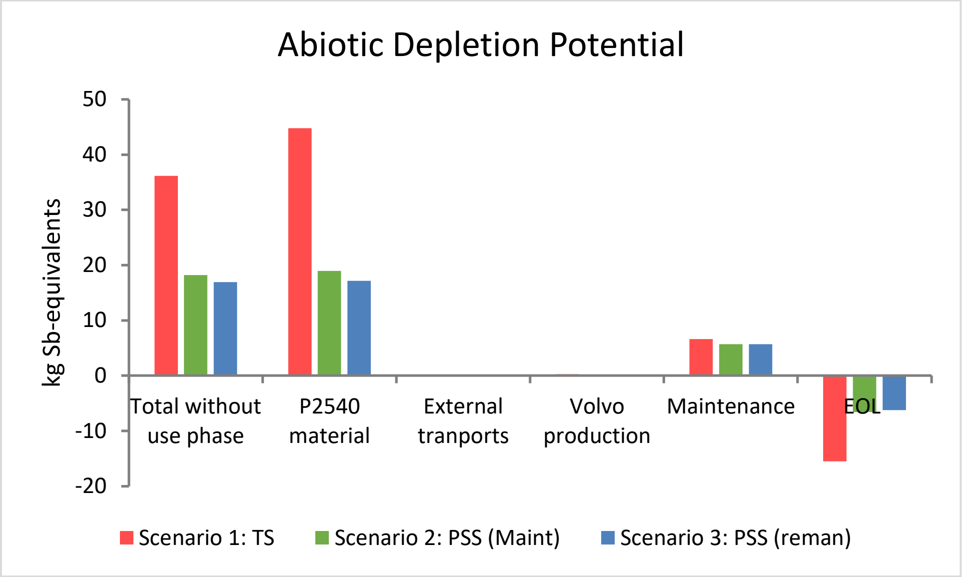

Figure 22. Abiotic Depletion Potential in Sb-equivalents for truck production, maintenance and end-of-life in three scenarios.

Table 20. Abiotic Depletion Potential in Sb-equivalents in a fleet maintenance condition.

Maintenance in fleet	**Scenario 1**	**Scenario 2**	**Scenario 3**
Total maintenance	6.636752	5.726848	5.726848
Corrective maintenance	8.271961	7.030341	7.030341
Preventive maintenance	0.210236	0.290436	0.290436
Maintenance EOL	-1.84544	-1.59393	-1.59393

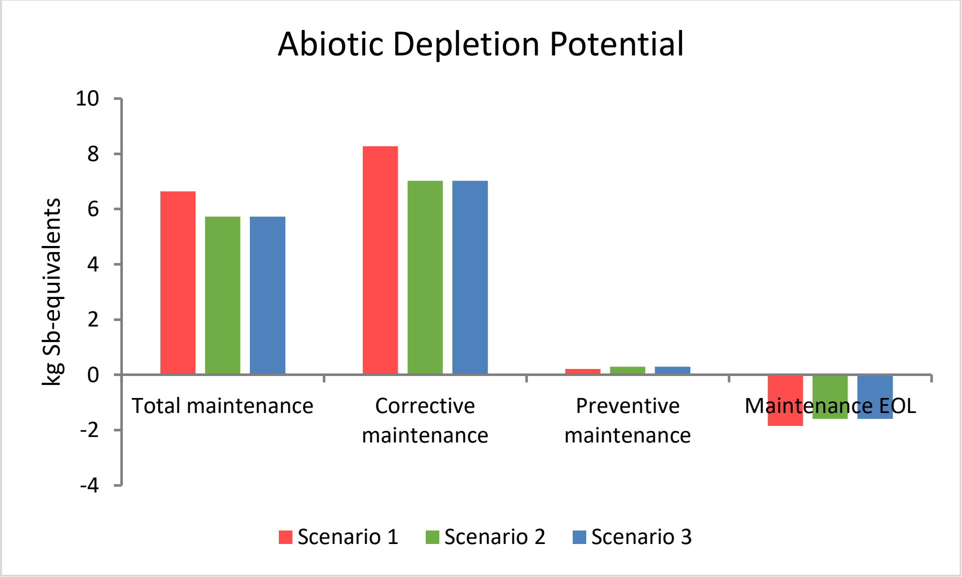

Figure 23. Abiotic Depletion Potential in Sb-equivalents in a fleet maintenance condition.

Table 21. Acidification Potential in SO2-equivalents for truck production, maintenance, fuel consumption and end-of-life in three scenarios.

Comparison between business models	Scenario 1	Scenario 2 (Maint)	Scenario 3 (Reman)
Total	114172.2	108250.4	108129
Production	15284.94	6476.67	6330.638
Fuel consumption	101838.9	101838.9	101838.9
Maintenance	2348.98	2180.843	2180.843
EOL	-5300.64	-2246.03	-2221.32

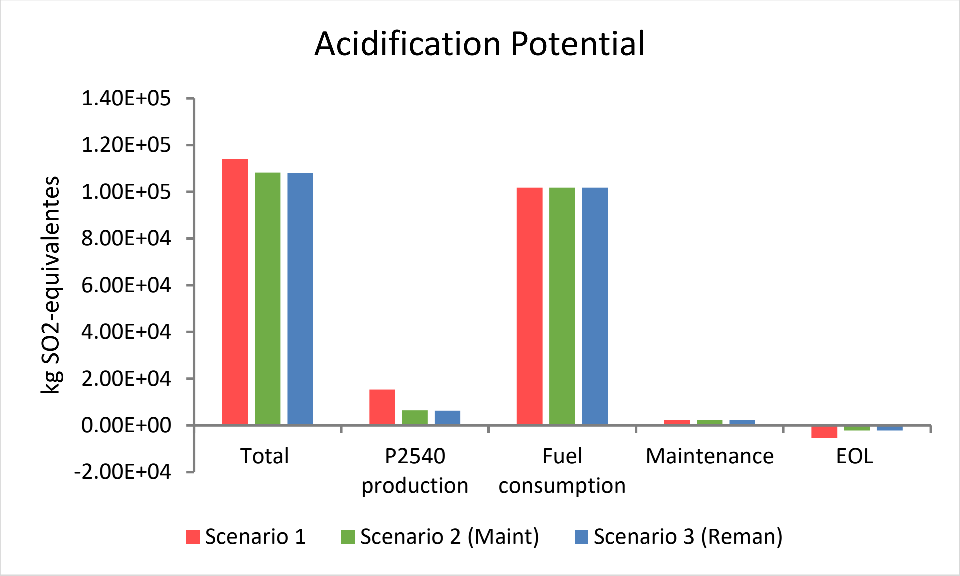

Figure 24. Acidification Potential in SO_2-equivalents for truck production, maintenance, fuel consumption and end-of-life in three scenarios.

Table 22. Acidification Potential in SO_2-equivalents for truck production, maintenance and end-of-life in three scenarios.

Comparison between business models	Scenario 1	Scenario 2 (Maint)	Scenario 3 (Reman)
Total without use phase	12333.29	6411.481	6290.156
Production	15284.94	6476.67	6330.638
Maintenance	2348.98	2180.843	2180.843
EOL	-5300.64	-2246.03	-2221.32

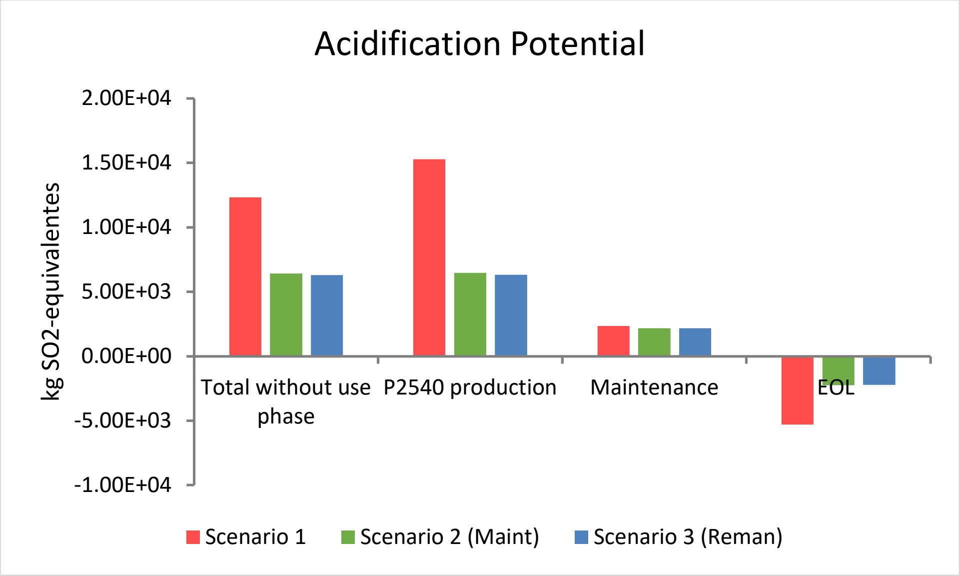

Figure 25. Acidification Potential in SO_2-equivalents for truck production, maintenance and end-of-life in three scenarios.

Table 23. Acidification Potential in SO_2-equivalents in a fleet maintenance condition.

Maintenance in fleet	**Scenario 1**	**Scenario 2**	**Scenario 2**
Total maintenance	2348.98	2180.843	2180.843
Corrective maintenance	2631.375	2435.401	2435.401
Preventive maintenance	99.88874	108.8267	108.8267
Maintenance EOL	-382.284	-363.385	-363.385

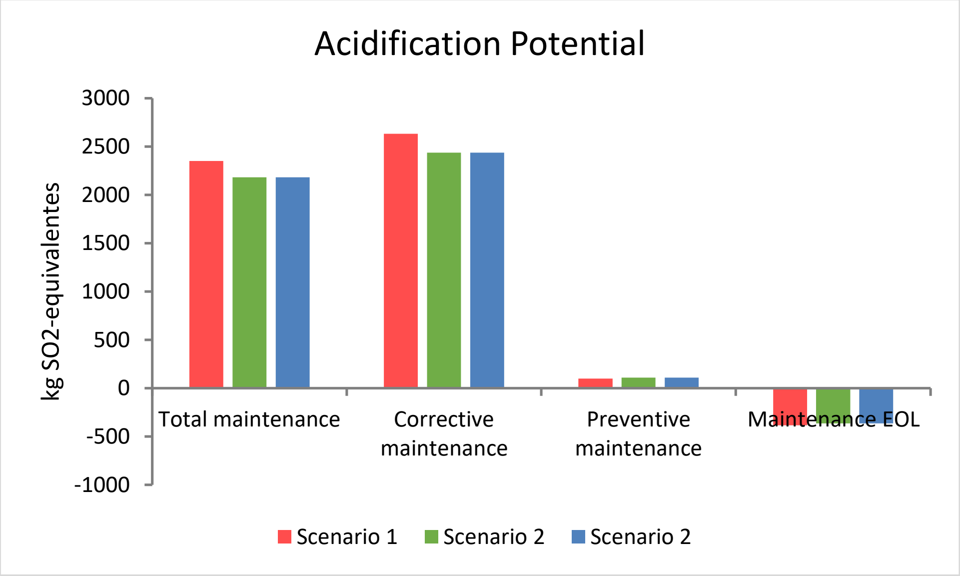

Figure 26. Acidification Potential in SO_2-equivalents in a fleet maintenance condition.

Table 24. Human Toxicity Potential in CTUh for truck production, maintenance, fuel consumption and end-of-life in three scenarios.

Comparison between business models	**Scenario 1**	**Scenario 2 (Maint)**	**Scenario 3 (Reman)**
Total	8.950504	8.623988	8.584813
Production	0.795382	0.337026	0.288919
Fuel consumption	8.326927	8.326927	8.326927
Maintenance	0.063265	0.059641	0.059641
EOL	-0.23507	-0.09961	-0.09067

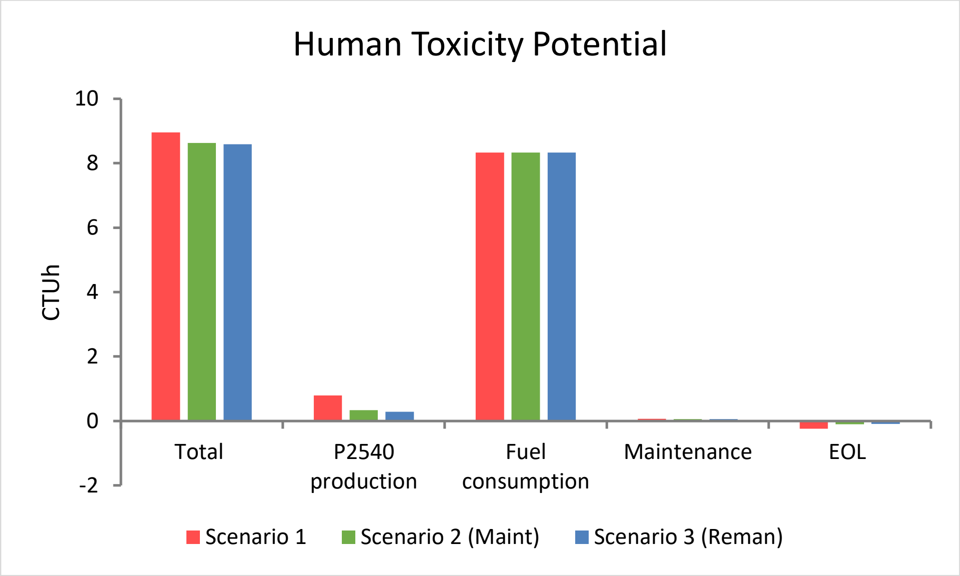

Figure 27. Human Toxicity Potential in CTUh for truck production, maintenance, fuel consumption and end-of-life in three scenarios.