Environmental Impact Assessment of Augmented Reality Technology Implementation

Master's thesis in Sustainable Energy Systems

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Department of Space,Earth and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021

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Abstract

Sustainability has a been a buzz word for a long term since the inception of the Brundtland commission. With the Paris agreement in 2016 and the on-going climatic changes have all lead to one solution, i.e., sustainability. On the other hand, the fourth industrial revolution that was spoken about back in 2011 has taken off widely with the use of robotics, machine learning, system integration, and big data. This has steered industries to use new techniques to be incorporated like sustainable manufacturing. There are a lot of technologies under Industry 4.0, one such device that is considered here is Augmented Reality. The technology is very useful as it can reduce human errors and help inexperienced technicians to work efficiently with the help of all preloaded data in its cloud library. There has been very less research in the field of LCA on AR devices. This study focuses on the environmental impacts during the life cycle of the AR device and the environmental benefits of using AR technology.

We have adopted a mixed approach as the methodology for this study. A string of interviews and literature study has been performed to conduct a LCIA study with the help of OpenLCA software. By the end of the research, the readers can find the results accomplished from the Life cycle assessment study such as the environmental benefits and consequences. Transport sector, shipping, is found to be the biggest concern in terms of environmental loads. Climate change is one impact category which is disturbed very much due to the transport sector.

The method and results aid the stakeholders and the actors to evaluate its sustainable performance in the implementation of AR in remanufacturing process and the impacts to the environment. By adding a few data gaps in the current study, this study can help to a wide extent in improving the efficiency of processes. reduce human error and inexperience at the manufacturing sector. Furthermore, sensitivity analysis is carried out to find critical variables that affect the feasibility of our results. Finally, recommendations are also provided where the environmental impacts can be minimised.

Keywords: Environmental Assessment, Augmented Reality, Re-manufacturing, Microsoft HoloLens-2.

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Balamurugan Jayakumar, Muhammed Rizwan Aboobacker, Göteborg, June 2021

Abbreviation

AR	Augmented Reality
VR	Virtual Reality
UN	United Nations
SDG	Sustainable Development Goals
EoL	End of Life
LCA	Life Cycle Assessment
LCIA	Life Cycle Investment Assessment
FU	Functional Unit
HUD	Head-Up Displays
PM	Particulate Matter
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
HTP	Human Toxicity Potential
MOIR	Maximum Ozone Incremental Reactivity

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1

Introduction

The transition from traditional manufacturing practices to sustainable manufacturing practices is being studied and practiced on an industrial level, to improve an organization's negative imprints on environment. The industrial revolution has played a pivotal role in human civilization, it has helped in bringing a sustained growth in the economy of a country. Currently, we are in the midst of the fourth industrial revolution called Industry 4.0 or I4.0. This change is propelled by nine new technologies (Lavingia and Tanwar, 2019) and Augmented Reality is one among them. Augmented reality (AR) has been used widely in the field of education, entertainment, tourism and fashion (Berryman, 2012). AR in industry will revolutionize industries by increasing efficiencies and producing fewer defective products (Chang, Ong and Nee, 2017).

Sustainability, the co-existence of biosphere and human civilization, is deemed to make a better and sustaining future for the coming years and generations. Following this, sustainable development has turned out to be the current trend in many industries and organizations. The importance of sustainability has been focused since the inception of the brundtland report (Brundtland, G.H. et.al., 1987) by the United Nations (UN). Remanufacturing, is one such tool that focuses on sustainability, improving the resource efficiency, reducing waste and promoting Circular Economy (Kerin and Pham, 2019). Re-manufacturing reduces negative impacts on the environment and promotes sustainable productivity (Jun et al., 2019). The process of disassembly in re-manufacturing is considered to be a tedious and difficult process which requires a lot of experience and knowledge to carry out. AR is known for giving the correct information at the right time and the right place, this can help in reducing the errors in the error prone disassembly process (Kerin and Pham, 2019). This is achieved by transferring the knowledge gained by previous experiences and uploading it into a database accessed by the AR technology. According to Chang et al, (2017) a preliminary product disassembly framework guided with AR has been studied and that has lead to efficient and error-free disassembly process.

The UN has framed the Sustainable Development Goals (SDG) as a way to achieve sustainable development in all aspects, these goals are aimed at making a better and more sustainable future for all by 2030. Remanufacturing is one such technique where the open life cycle of a product is closed by remanufacturing the product with just the missing and irreparable parts/components. According to Liu et al. (2014), remanufacturing increases resource efficiencies and promotes cleaner and more sustainable production. AR is an extension of virtual technology, where the computers help in imprinting the virtual world into the real world and bridges the gap between the two worlds (Azuma, 1997).

Quality, Safety, and Environment has been a part of the heritage and identity of Volvo group. Volvo, being an avid supporter of sustainability by focusing on climate and resources. With the commitment to the Paris agreement, Volvo has set a target to achieve net-zero emissions by 2050 and developing products and solutions that reduce the CO2 footprint. It has plans to replace fossil power with sustainable energy sources such as wind, solar, biomass and bio fuels. Volvo is also reconsidering its production and consumption patterns and has increased its focus on circularity which is deemed to result in improved environmental resources management and materials efficiency with significant cost-saving opportunities. Volvo Group Trucks Operations Power train Production at Flen is currently being shifted to a new location and the organization is considering the implementation of Augmented Reality in its re-manufacturing line. With its avid involvement in sustainability, the environmental study of the AR implementation is studied here.

With the ongoing upgrades for Industry 4.0 revolution, augmented reality, already being used in lots of fields, is introduced into industries to reduce the errors and improve the efficiencies as mentioned previously. Here, AR is introduced in the assembly and disassembly section of the re-manufacturing unit of Volvo plant. According to Chang et al, (2017) a preliminary product disassembly framework guided with AR has been studied and that has lead to efficient and error-free disassembly process.There is also very less study in the field of Augmented reality and studies have slowly and rapidly taken interests in AR in the last decade. This sudden raise is contributed to the potential improvement in maintenance, assembly sectors. (Bottani and Vignali, 2019).

1.1 Project Aim

The thesis project aims in conducting a life cycle analysis and quantify the environmental impacts of implementing a AR device in a engine remanufacturing process.

1.2 Project Limitations

The term sustainability rests on three pillars: economic, society and environment. With time constraint and scope being a factor in carrying out in this project, only environmental sustainability is considered in this project.

The scope is restricted only to the AR devices and the engine re-manufacturing process is only part of the life stage of AR, i.e., it is the use phase of AR devices in remanufacturing process.

1.3 Research Question

Regarding the purpose and target, a research question was formed. The below research question will be answered through this project.

RQ: What are the environmental impacts of the life cycle of AR Devices implemented in the engine re-manufacturing process?

This question analyses the environmental impacts posed by the AR devices. The question considers all the processes and stages in the life cycle of the AR devices. The main consideration is given for the life cycle of AR devices that are to be implemented to the engine remanufacturing process.

2
Theory

In the following sections, terms like sustainability, circular economy, augmented reality, life cycle analysis are discussed in details with respect to the scope of the study. Also the augmented reality device, HoloLens-2 is also discussed in detail in this section.

2.1 Sustainability

Sustainability is playing a pivotal role in the current industrial advancements with cleaner production, pollution control, eco-efficiency, environmental management, social responsibility, industrial ecology, ethical investments, green economy, eco-design, reuse, sustainable consumption, zero waste. Sustainability is defined and understood in many by various organizations and literature. According to the brundtland report (Brundtland, G.H. et.al., 1987), it is defined as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Sustainability has been synonymous with three dimensions or pillars, social sustainability, economic sustainability, and environmental sustainability (Alipour and Galal Ahmed, 2021).

Linear manufacturing contributes to a high share of manufacturing processes currently used. This technique contributes to a high share of waste, low energy efficiencies, pollutants and emissions which are raising a lot of concerns in the current environmental perspective. Low efficiencies, resource depletion, green gas emissions, governmental policies are the constant challenges faced by linear manufacturing techniques (Abokyi, Appiah-Konadu, Abokyi and Oteng-Abayie, 2019). One such sustainable manufacturing technique is circular economy, which focuses on reducing waste and closing the loop.

Since the publication of the Brundtland report, sustainability has become a huge perspective industry. With this the UN have drafted 17 sustainable development goals (SDGs) (United Nations, 2015) in its action plan for "2030 Agenda for Sustainable Development" to improve sustainability in areas like people, planet, prosperity, peace, and partnership.

2.1.1 Circular Economy

Circular economy (CE) has been found to be an excellent strategy to various sustainable development goals (Schroeder, Anggraeni and Weber, 2018). CE, according to MacArthur .E (2013) is defined as “the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems”. The concept of CE focuses on closing the linear loop, slowing the use of resources and increase the efficiency of resources, materials, and energy used (Hobson, 2020). The 6R concept - Reduce, Reuse, Recycle, Redesign, Recover, and Re-manufacture (Jayal, Badurdeen, Dillon and Jawahir, 2010) is a technique used in circular economy. The 6R concept enables to achieve sustainable manufacturing by recovering end-of-use/end-of-life products for closed-loop manufacturing cycle (Enyoghasi and Badurdeen, 2021). With the current industrial revolution 4.0, sustainable manufacturing can play a huge role by closing the loop and increasing the efficiency of the resources and product.

2.1.2 Remanufacturing

Remanufacturing aids in achieving cleaner and more sustainable production of products at low cost and reduced waste (Kerin and Pham, 2019) (Jun et al., 2019). Remanufacturing is a technique which circumvents the additional resource investments and environmental impacts related with the production of a new component (Adler, Ludewig, Kumar and Sutherland, 2007). The general procedure of remanufacturing starts with the End of Life (EoL) products or components followed by disassembly, cleaning, inspection, restoring of defective parts, replace vulnerable and non-remanufacturable parts, reassembly, and testing, in order (Zheng et al., 2019).

The following figure 2.1 shows the remanufacturing line at Volvo, Flen plant. First the product in End of life (EoL) is dissembled. Disassembly is the most complex and a strenuous process in the whole remanufacturing activity. The components that are mostly worn out and commonly remanufactured are cylinder head, cylinder block, crankshaft, connecting rod, and camshaft. The components then undergo heat and water treatment with subsequent quality checks in the middle to identify any defects that are irreparable and sent to scrap. Periodic Quality Control (QC) steps are undertaken at the end of each process to ensure the best parts are taken into the next process in the re-manufacturing process. The burned oil in the engine parts makes it hard to identify the defects, and heat and water treatments helps in solving this issue. At the reassembly, at least 30% of components are new components.

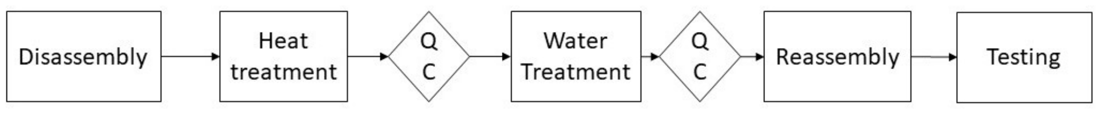


Figure 2.1: Activities in Remanufacturing Process at Volvo Flen Plant

2.2 Augmented Reality

Industry 4.0 refers to the fourth industrial revolution, which uses computerization and information to increase the experience and efficiency of manufacturing processes (Lavingia and Tanwar, 2019). The figure 2.2 shows the timeline of all the previous industrial advancements from steam power to robotization.

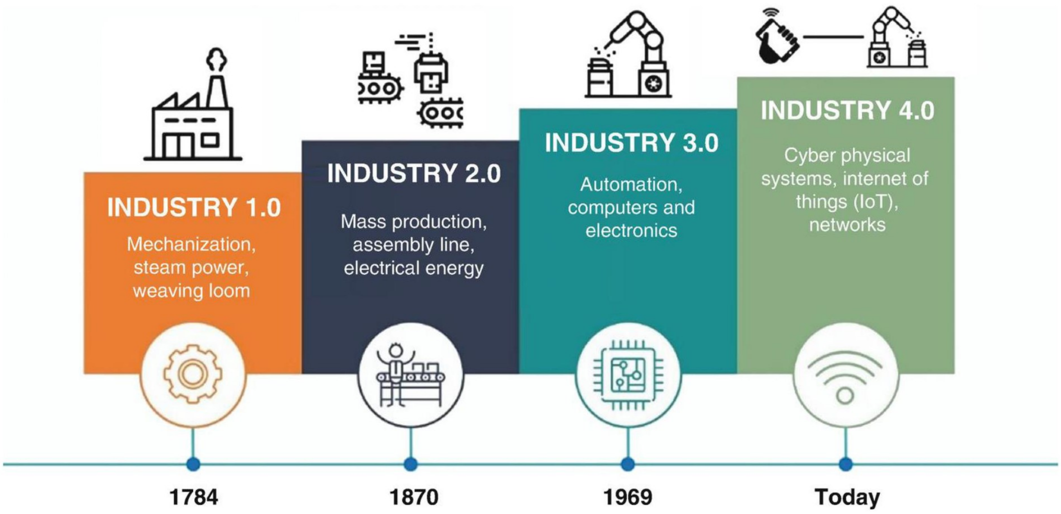


Figure 2.2: Evolution of Industrial revolution, Source: Lavingia and Tanwar, (2019)

According to Batth (2018), Industry 4.0 is driven by nine new disruptive technologies, they are cybersecurity, AR, automated robot, system integration, simulation, big data, additive manufacturing, distributed computing, and the Internet of Things. AR is one the technological innovation that is driving the Industrial Revolution 4.0. Industry 4.0 technologies help in reducing the cost of production, shorten the processing time, improved customer service, high flexibility in processes and product customization (Fettermann, Cavalcante, Almeida and Tortorella, 2018). I4.0 technologies helps in attaining sustainable and green manufacturing ideologies like circular economy and smart factories.

Augmented reality is a technology that helps in super imposing the virtual world onto the real world, thus creating a new user experience. This aims at bridging the gap between the real and virtual world. AR has been widely used in entertainment, training, libraries, education, tourism, and marketing. With this, manufacturing companies are using it in their supply chain and logistics to provide the right information at the right time to improve the efficiencies of the processes. Some of the most common devices that are used to experience AR are Head-Up Displays (HUD), holographic displays, smart glasses like Halolens, Meta 2 glass and google glasses, hand-held displays like smart phones or tablets.

2.2.1 Types of Augmented Reality

Augmented Reality technologies are classified into various types (IPCS, 2021):

Marker-based AR: This type of AR device uses picture conformation of specific QR codes or unique sign to give related information. The QR code or signs acts as markers and hence the type is called marker-based AR.
Marker-less AR: Here, location-based information is used with the help of Geo-Positioning System (GPS) to provide information with respect to the location.
Projection-based AR: These are multi-dimensional pictures that are used in science fiction films. These are type of holograms that can be projected on surfaces. For example, projecting different shoe designs on a shoe model for customers.
Superimposition-based AR: This type replaces the main object with its augmented twin. Example: IKEA Catalog application.

2.2.2 Microsoft Hololens 2

For the integration of the AR technology in the engine remanufacturing line, two types of devices are considered: Handheld (2019 IPad Pro) and wearable smart glasses (Microsoft Hololens 2). The major focus in this project is on the Microsoft Hololens 2 as it is the possible choice for implementation. Hololens 2 is the second generation of the mixed reality smart glass developed and manufactured by Microsoft Corporation. It was announced in 2019 during the mobile world congress in Barcelona, Spain.

Figure 2.3: Microsoft Hololens 2, Source: Microsoft HoloLens, Mixed Reality Technology for Business, (2021)

Hololens-2, figure 2.3, is a head mounted display that has a wearable, adjustable-cushioned headband. In front section of the device holds the sensors, processing unit and the display while the battery and the size adjustment mechanism of the headband are located at the rear of the device. The physical buttons to turn on/off the power and to control the volume are located at the centre near to the ears. The front of the device has a pair of tiltable visors which encloses the display as well. Among the sensors that are incorporated in the Hololens is an Inertial Measurement Unit(IMU) that has an accelerometer, gyroscope and a magnetometer, four eye tracking cameras (two on each side), a depth sensing camera, a RGB camera and an array of four microphones. The total weight of the device is 566g. The detailed technical specifications (HoloLens 2 hardware, 2021) of the device are mentioned in the table 2.1 below:

Optics	See-through holographic lenses (waveguides)
Holographic resolution	2k 3:2 light engines
Holographic density	>2.5k radiants (light points per radian)
Eye-based rendering	Display optimization for 3D eye position
Head tracking	4 visible light cameras
Eye tracking	2 Infrared (IR) cameras
Depth	1-MP Time-of-Flight depth sensor
Inertial measurement unit (IMU)	Accelerometer, gyroscope, magnetometer
Camera	8-MP stills, 1080p30 video
Microphone array	5 channels
Speakers	Built-in spatial sound
System on chip	Qualcomm Snapdragon 850 Compute Platform details
Holographic processing unit	Second-generation custom-built processing unit
Memory	4-GB LPDDR4x system DRAM
Storage	64-GB UFS 2.1
WiFi	802.11ac 2x2
Bluetooth	5
USB	USB Type-C DRP
Battery Life	2-3 hours of active use. Two weeks of standby time.
Battery technology	Lithium batteries
Charging behavior	Fully functional when charging
Cooling type	Passively cooled (no fans)

Table 2.1: Technical specifications of Microsoft Hololens-2, Source: HoloLens 2 hardware, (2021)

2.3 Life Cycle Assessment

Life Cycle Assessment is a comprehensive method to study the environmental impacts of products and services. It is one of the many environmental procedures that were used to along with others like Environmental Impact Assessment (EIA), Ecological Risk Assessment (ERA) and others. The major difference between LCA and other procedures is that LCA is analyses impacts throughout the product life cycle. (Baumann and Tillman, 2004)

According to ISO 14040 (2006), LCA is defined as a "technique of assessing the environmental aspects and potential impacts associated with the product by compiling an inventory of relevant inputs and outputs of a product system followed by evaluating the potential environmental impacts associated with the inputs and outputs of a product system and concluded with interpretation of results of the inventory analysis ".

2.3.1 LCA Framework

LCA methodology has gone through evolution since its inception and the current methodology is as per the standard ISO 14040 (2006) which is presented in the figure 2.4

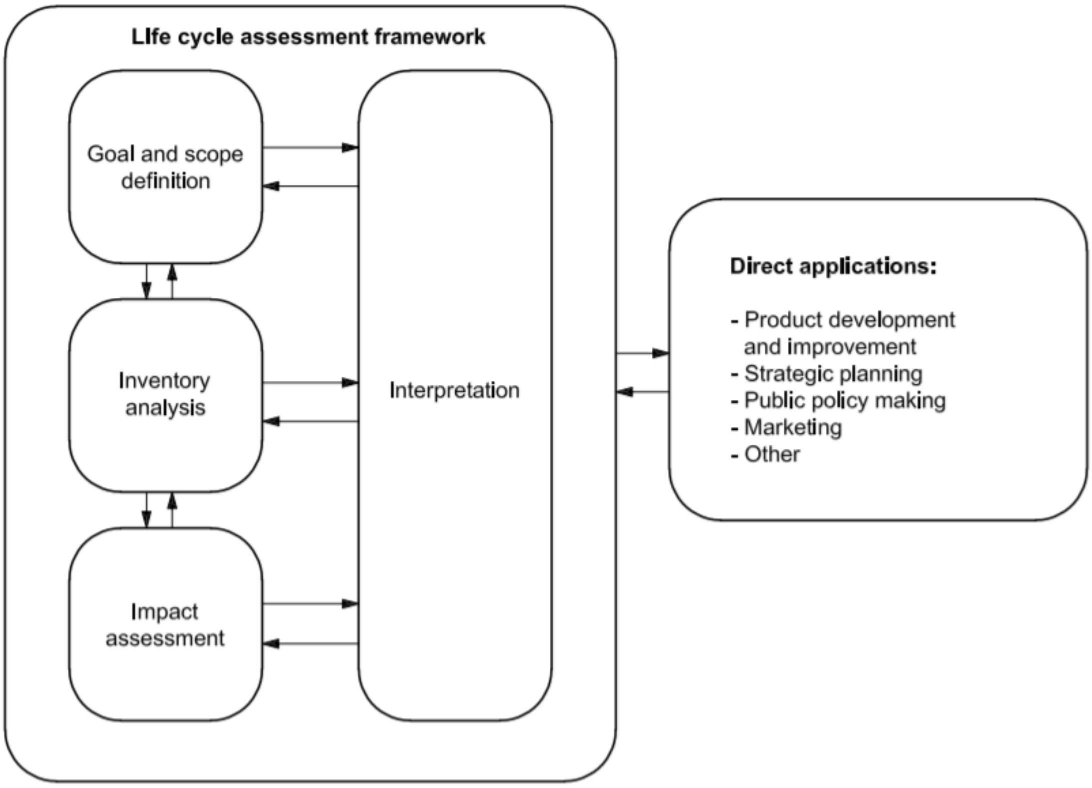


Figure 2.4: LCA Framework, Source: ISO 14040 (2006)

Goal definition and Scope

The goal definition and scope are the first step of a LCA study. They answer the reason and the purpose for the study to be carried out in the first place. According to ISO 14044 (2006), the goal definition of LCA "shall unambiguously state the intended application, the reason for carrying out the study and the intended audience". The scope pertains to the variables that are essential in modelling the study in the best desired way possible. The variables are functional unit, system boundaries and the choice of impact categories.

Functional Unit: According to ISO 14040 (2006), functional unit is defined as "quantified performance of a product system for use as a reference unit". It serves as a reference in which the inputs and outputs of the all activities in the product life cycle are related.

System boundaries: The boundaries refer to the scope within which the study is carried out. The boundaries are further classified into boundaries with relation to natural systems, geographical boundaries, time boundaries and technical systems. These boundaries help in establishing the extent to which the study is carried and the factors that are affected.

Inventory analysis

The activities of inventory analysis involve construction of flowchart according to the system boundaries decided in goal and scope definition followed by data collection of all activities in the product life cycle and documenting them. The data here is all the input data like fuel, raw materials and output data like finished product, waste, and emissions.

Impact assessment

The impact assessment involves transforming the environmental loads into environmental impacts like resource use, human health, and ecological consequences. The environmental loads are categorised further like global warming, ozone depletion, toxicity, acidification, eutrophication and make interpretations of results easier. The impact assessment is further explained in a later section below.

Interpretation

In this phase, based on the inventory analysis and impact assessment the potential areas of improvement are identified. The results from the LCI and LCIA of a product or process are represented systematically to identify and evaluate the information to present them in a document to meet the requirements mentioned in the goal and scope of the study. A set of different type of analysis like contribution analysis, dominance analysis, break even analysis, decision-maker analysis can be made. Also, the robustness of the results can be found out by using the sensitivity and variation analysis.

2.3.2 Life Cycle Impact Assessment Methods

According to ISO 14040 (2006), Life Cycle Impact Assessment (LCIA) is a phase of LCA where the magnitude and importance of the environmental impacts of the product system are evaluated. The enormous data regarding material flow, resource consumption, energy usage, and emissions make it difficult to obtain the LCA results, hence the aggregation of the impact category results are essential to obtain the systematic results.

The data from the inventory analysis is categorised based on the characterisation of environmental impacts caused by the environmental loads. Followed by this technique like normalisation, grouping, and weighting are used to calculate extent of impact of each category and group them. There are also several readymade LCIA methods that are widely used like ECO-Indicator 99, EDIP, USES-LCA, IPCC 2007, CML 2001, BETR, ReCiPe. (Baumann and Tillman, 2004)

ReCiPe is the tool used in this thesis as a method to conduct the impact assessment. According to (Acero, Rodríguez and Ciroth, 2017), the method focuses on combining the method that has been used in the Eco-Indicator 99 and CML databases. ReCiPe uses two levels of indicators, midpoint indicators (18 indicators in total) and endpoint indicators (3 indicators in total). The midpoint indicator level focuses on the single environmental issues while the endpoint indicator level focuses three areas such as damage to human health, damage to ecosystems and damage to resource availability. The indicators are further categorised based on three cultural perspectives. They are Individualist (short-term), Hierarchist (default model) and Egalitarian (long term) (Huijbregts et al., 2016). The figure 2.5 shows the various indicators of ReCiPe.

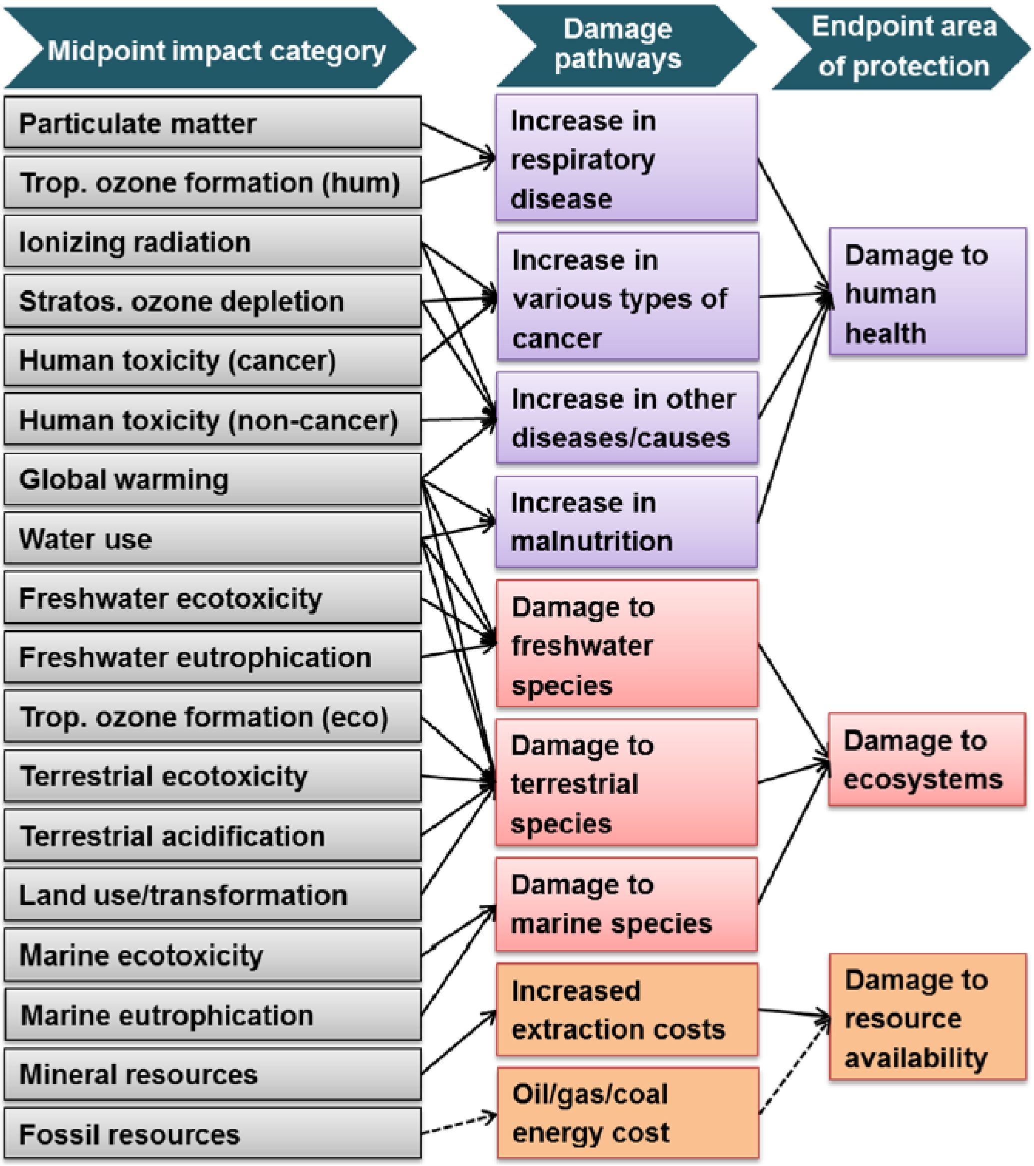


Figure 2.5: Overview of the impact categories in ReCiPe2016, Source: Huijbregts et al., (2016)

2.3.3 OpenLCA

OpenLCA, is a open source and free software for Life Cycle Assessment, which used as impact assessment tool in LCA studies. The investments are very low in OpenLCA compared to other LCIA tools. The data sheets are also available online and are downloadable (Silva et al., 2017). It is created by greendelta and the code for the software is opensource. OpenLCA supports both environmental impact assessment models as well as the economic assessment models. It has various impact assessment methods such as CML baseline, ReCiPe 2016 etc. present in the software and the databases such as Ecoinvent, ELCD etc. which is available as package that can be downloaded from Greendelta and then imported into the projects. It also provide different kind of analysis methods such as Monte-Carlo simulation.

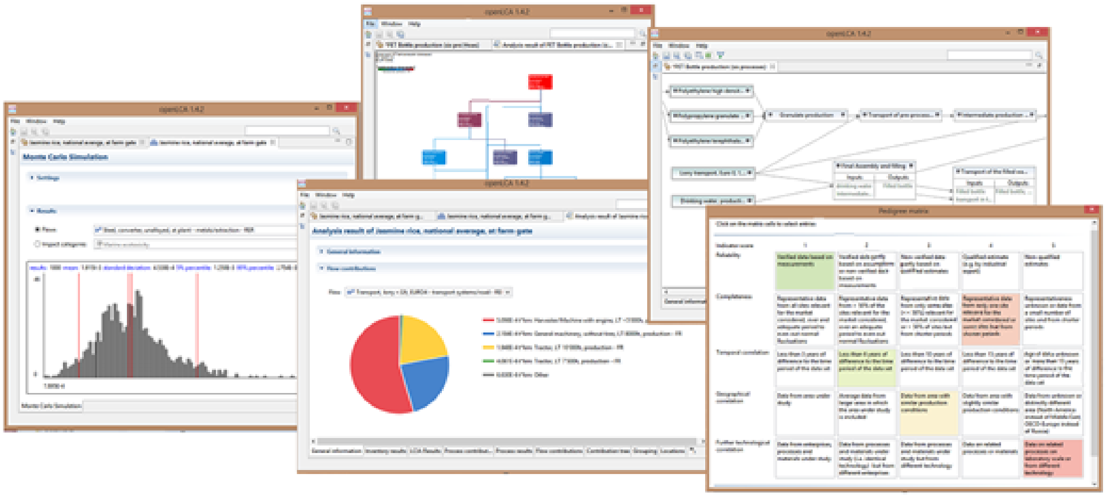


Figure 2.6: Overview of OpenLCA, Source: (OpenLCA,(2021)

2.3.4 Life cycle impact categories

To answer with the goal of this study the following environmental impact categories are selected such as energy and material use, Global warming potential (GWP), Acidification potential (AP), Human toxicity potential (HTP), Marine eutrophication (MEP), Water depletion (WDP), and Particulate matter formation (PMFP).

Energy and material use:
The amount of energy and material consumption during each activity to achieve the product or process. Here energy is in the form of electricity, pressure, thermal requirements, fuel and water requirements.

Global Warming Potential (GWP):
The global warming potential measured over different time horizons that are set by the UN Intergovernmental Panel on Climate Change (IPCC). GWP is presented in terms of kg CO2 equivalents. The substances contributing to the GWP are gases that absorb infrared radiation like carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs). These substances cause a change in the global temperature and the rise of the global temperature leads to climate disturbances, desertification, and cause for diseases. The different time horizons in calculating GWP are 20years, 100 years and 500 years. Among these, GWP100 is the most sought out method.

Acidification potential (AP):
Acidification potential is measured in kgSO2 equivalents. Substances contributing to the acidification potential are ammonium, nitrogen oxides, hydrochloric acid and sulphuric acid. These gases are trapped in the atmosphere by clouds which results in acid rain and affects the pH values by making the ecosystem more acidic in nature.

Toxicity:
Toxicity is a difficult factor to measure as it can spread throughout the ecosystem. Heavy metal like mercury, lead, and pesticides and organic solvents can cause different toxic components that are complex. To make this easier, the toxicity is categorised further into human toxicity and eco-toxicity. Eco-toxicity is further divided to aquatic and terrestrial toxicity. Aquatic toxicity is classified to freshwater and marine toxicity. The toxicity potential is given by the following formula.

Photochemical Ozone Creation Potential:
The secondary pollutants formed in the lower atmosphere from nitrogen oxides and hydrocarbons in the presence of sunlight. This results in photo-chemical smog which results in severe respiratory issues and harm to vegetation. Thus, the photo oxidant creation potential is an important factor to measure. The difference in NOx concentration leads to complexity this has led to using High-NOx, High-POCPs, Low-NOx and Low-POCPs.

3
Methodology

A mixed approach, qualitative and quantitative, is chosen to answer the research question in a synergistic manner. The qualitative approach consists of the literature study, and case study. The case study consists of interviews with personal of an organisation, internal documents, and observations. The Quantitative approach deals with any experiment or testing, here a LCA study is carried out to find the environmental impacts that are required to be found with the implementation of AR device. The methodology is divided into four sections *(i) (i) Qualitative Approach, (ii) Quantitative approach- LCA analysis (iii) Results (iv) Interpretation.* An overview of the method followed in this thesis can be found in following figure 3.1.

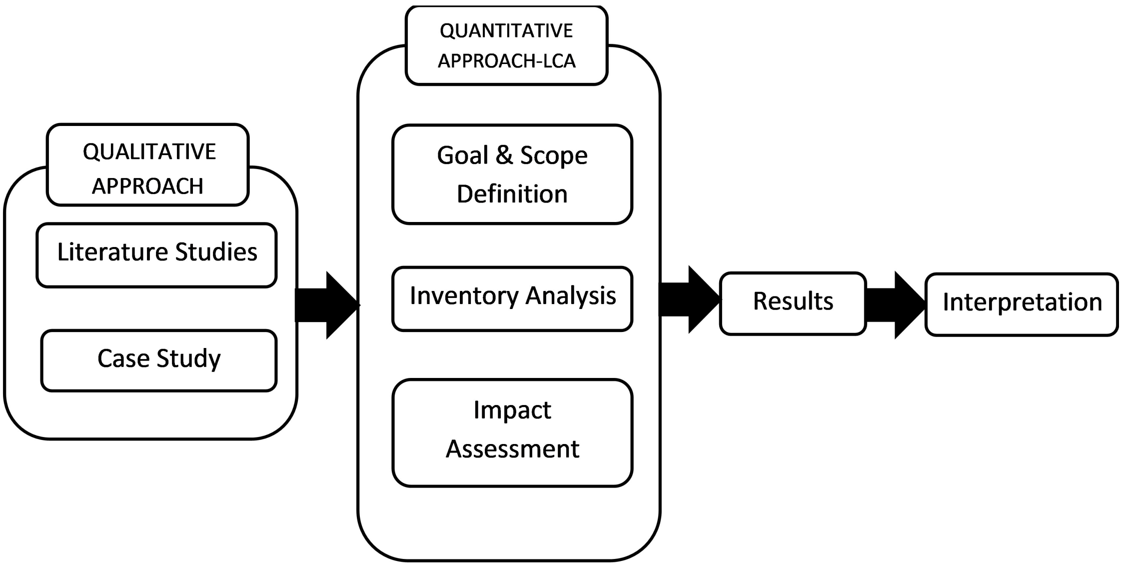


Figure 3.1: Adopted Methodology(Flow diagram)

3.1 Qualitative Approach

The data collection process is carried out through a qualitative approach in two ways for this thesis, literature studies and case study. A case study approach is used here because three out six sources mentioned in (Yin, 2009) are used here. Yin (2009) also explains that not all sources are applicable for all case studies. The sources that were used in this case study were interviews, internal documents and observations. Interviews were carried out with Volvo personnel and researchers at the University of Skövde and Chalmers University of Technology to learn about the current trends in both research and industrial setup of AR in remanufacturing site. Literature studies were carried to gain background information and have a better understandings of the various technologies and procedures carried out in the thesis

3.1.1 Literature Studies

The preliminary idea behind carrying out a literature study is to understand the technologies and studies that are currently being carried out in the technologies and supporting fields that are studied in the thesis. Scopus was the most sort after search engine that was used in finding research papers followed by Chalmers library. A few findings from both the search engines redirected to other Sciencedirect, Springer Journals, and Researchgate. The keywords that were focused during the literature study were Augmented reality, Remanufacturing, Industry 4.0, Sustainability and Life Cycle Assessment. Using the Boolean operators like "AND, OR" we used a series of combinations like *"Augmented reality AND Remanufacturing"*, *"Augmented reality AND Remanufacturing"*, *"Remanufacturing AND Industry 4.0"*, *"Sustainability AND Augmented Reality"*. These combinations yielded a total of 15,674 search results.The found literatures were grouped under the categories. of title, area of use, database, search word, applied filter, number of hits, date for search and year. The abstracts of the selected journals were read and then further categorised with feasibility of the study by grouping under categories like AR, sustainability and LCA. By removing the repeated documents, the total results were shortlisted to 175 research papers. By reading the abstract, the total was reduced to 90 papers. It was clear from the readings that the research on augmented reality was very less, specifically the research of AR devices in remanufacturing process. To widen the search, we then added keywords like Circular Economy and Sustainable manufacturing. The research papers also proved to be useful in using some secondary data that were not available from primary sources. Furthermore, some websites related to the United nations and the European Union and websites linked to Swedish Agencies were also looked upon to gather data to perform the tasks.

3.1.2 Interviews

Three interviews were conducted with personals, who have better knowledge and who are working with technologies and processes that are used in pursuit to find an answer to the presented research question. Interviews were carried out with a researcher at the University of Skövde has been working in the field of augmented reality. Further information and knowledge were shared by another researcher at Chalmers who specializes in the field of AR and VR. Experts at Volvo who are working in the Advanced Research Engineering Recommendation Projects at Volvo and expert in the field of remanufacturing have also been interviewed.

The interviews have been conducted through emails and video conferencing due to the ongoing pandemic. A plant visit to Volvo, Flen plant or to the University of Skövde was not possible due to the same safety and health protocols mentioned previously. The interviews were semi structured, where qualitative information was gathered with pre-determined questions that were sent out before and the interviews were conducted for a period of 60 minutes.

Interview 1:

A video conference interview was held with a researcher at Chalmers University of Technology who specializes in the field of AR and VR at the SII-lab in the University. The interview focused on the basics of AR technology and gave a distinct explanation on the different AR technologies like wearable AR, hand-held AR technology and projection-based AR technology. The interview was followed by a few questions from us which are presented below.

1. What are the materials used for the construction of the AR device?
2. How is the device programmed for various purposes. Is there any external hardware or sensors used according to the purpose of the device?
3. What type of sensors are inbuilt in the device and what are the defining characteristics of a good AR device?
4. Do the materials of construction differ from device to device or all the devices possess the same features?

Interview 2:

The research work of AR implementation in a remanufacturing line is currently being done at the University of Skövde as a part of Rewind project along with Chalmers University of Technology and the Volvo remanufacturing plant. The research worker has been working on AR implementation and has been running designs and simulations. A semi structured interview was carried out, with the motive to understand how the implementation is carried out. A scaled unit has been prepared at the University of Skövde and was demonstrated by the researcher during this interview. The workstation where and why the AR technology is needed to be implemented was discussed during the interview. The following questions were talked about at the end of the interview.

1. Why HUD type AR device is preferred over handheld AR device in the remanufacturing process?
2. Why Hololens-2 is preferred over other HUD AR technology devices?

Interview 3:

Two interviews, one video conferencing and one email interview, were conducted with professionals at Volvo. During the online interview, the professionals explained about the remanufacturing line that is currently being used at the Volvo GTO, Flen plant. The flow diagram of this process has been represented in 2.1. Following this an e-mail interview was carried regarding each activity that are performed in the remanufacturing line, the questions are presented below,

1. What is the average time in burning and washing station for an engine?
2. What is the average energy and water consumption for an engine in the burning

and washing station?
3. What is the average time in assembling and disassembling an engine?
4. What is the source of energy in the assembly and disassembly process (like electricity, compressed air etc.) ?
5. What are the energy usages in the assembly and disassembly for an engine?

3.2 Quantitative Analysis-LCA

The LCA study consists of three main parts,
1. Goal and Scope Definition
2. Inventory analysis
3. Impact assessment

Goal & Scope Definition:
In this section the entire scope of the study is explained. The parameters, variables, the boundaries and assumptions are all well defined in this section.

Inventory analysis:
The data collected from Volvo and the secondary sources have been sorted out according to the three stages in the life cycle of the Hololens 2. The life stage of the Hololens is divided into seven processes for the ease of calculations. They are, *(i)Manufacturing of the device, (ii) Shipping from China to Germany, (iii) Truck transport from Germany to Sweden, (iv) Use phase in Volvo engine remanufacturing unit, (v) Truck transport in Sweden to the waste treatment plant, (vi) Incineration of the waste and (vii) Landfilling of the waste after incineration*

Inventory analysis is done after the sorting of the data. First, the entire emissions and the raw materials quantity is converted in terms of the weight of the device. This value, that has all the inputs and emissions per device is then used for the Life cycle impact assessment(LCIA) in the OpenLCA software. The obtained results from the LCIA is then converted in terms of the functional unit. As mentioned earlier, it is assumed that a device will be used for at least 5 years in the remanufacturing line before its end of life.

Impact assessment:
The impact assessment is carried out using the OpenLCA software. The first step in the software was to create the database. A database named "Remanufacturing_LCA" was created in the software. All the products, outputs, inputs, emissions etc. is added to the flows section and the properties, both physical and chemical, were added. The next step was to create the processes. All the life stages of the device mentioned in the above part was added as separate processes with all the inputs and outputs with their respective quantities according to the inventory analysis. A product system named "LCA_on_AR" was created by linking all the processes and is mentioned in the appendix A.7.

The next step is to perform the impact assessment on the product system. The emissions from different stages of the life cycle were calculated using the data provided by the European reference Life Cycle Database (ELCD). This database was selected due to the reason that it comprises of genuine data that was collected from different sources such as EU business associations, energy carriers, transport organisations and waste management authorities. LCIA was done using the ReCiPe 2016 Midpoint method. The package for the LCIA method was downloaded from the GreenDelta website and then imported to the software. The LCIA was done and the results were extracted to MS Excel. The required data was sorted out and the picked up from the pile of results obtained. Acidification potential, Climate change, Human Toxicity, Ozone layer depletion potential, Photochemical oxidation was the impact factors considered. The LCIA was done for the device for the ease of calculation. Therefore the next step was to convert the obtained results in terms of the functional unit. Finally two sensitivity analysis are carried out to in terms of life of the device and the mode of transport used in the the study are analysed further in the report in the upcoming chapters.

3.3 Results & Interpretations

In this section all the results from the LCIA method are tabulated and graphs are made to make a comparative study. The environmental hot-spots and critical factors are found and analysed in this section. The impact values are analysed with the use of analysis strategies like dominance analysis and contribution analysis which are further described in the upcoming chapter.

4
Results

4.1 Goal & Scope Definition

The main aim of the project is to identify the environmental impacts of incorporating AR technology in a remanufacturing site. The site considered in this project is the Volvo GTO remanufacturing site located at Flen. The scope of the LCA is affected by a number of variables and they are presented as follows,

4.1.1 Flow Chart & Functional Unit

A draft flow chart is created initially with no regard to the boundaries and just the process and activities in involved in the study. The functional unit helps in calculating the environmental loads and impacts and compare it in a common value. Here the functional unit (F.U.) chosen is **per unit engine**. The following figure 4.1 represents the initial flow of processes that are involved in the study.

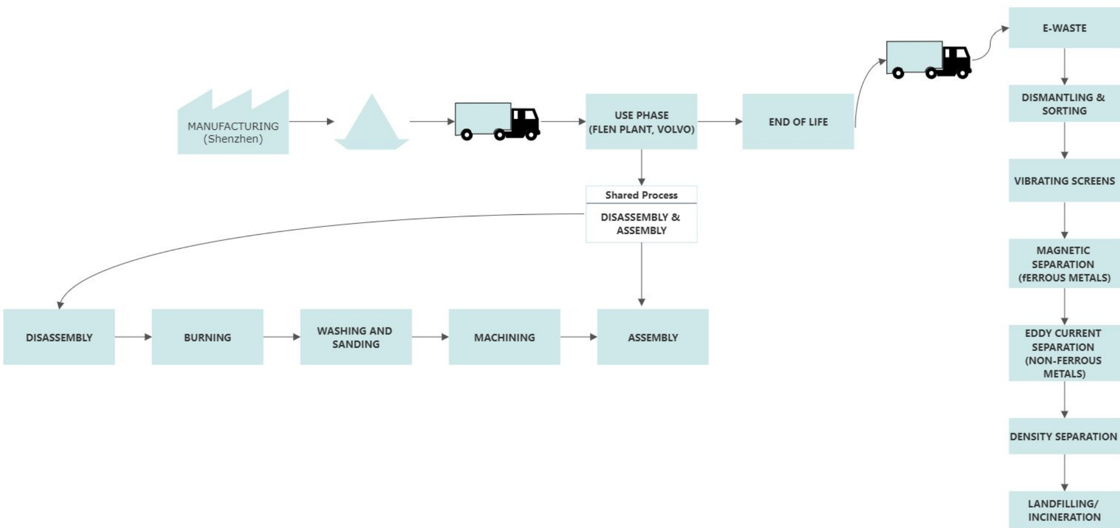


Figure 4.1: Initial Draft Flow chart of the intended product, HoloLens-2

4.1.2 Impact Categories

The impact categories used in the study are as follows,

1. Global warming (100 years)
2. Acidification Potential
3. Human toxicity
4. Photo chemical oxidant creation
5. Ozone layer depletion

The impact categories are chosen based on the type of pollution that has been considered affecting a lot to the environment. Air pollution and toxicity are the two main classifications that are discussed in this study. Acidification potential is used to measure the level of acidity in the air which causes acid rain. The Ozone layer depletion records the gases in the atmosphere that correspond to the depletion of the ozone layer of the earth. Climate change is most talked effect in any process or LCA study so the Global Warming Potential (GWP) is also considered in the study. The time horizon for GWP is taken as 100 years as it more standardised and gives more accurate results than 20 or 50 years (Why using 20-year Global Warming Potentials (GWPs) for emission targets are a very bad idea for climate policy, 2021). Finally Photo chemical oxidation potential and human toxicity impact categories are used in the study.

4.1.3 Type of LCA

The LCA study carried out cover activities from the raw materials used in the product to the end of life of the product, HoloLens-2. So the LCA study here is **cradle to grave** type of LCA study.

4.1.4 System Boundaries

Technical boundaries: Here the cradle of the study is the manufacturing part of the HoloLens-2 and the grave of the study is incineration and land filling. The fuel used in transportation come under the natural boundaries. The study considers emissions to air and water. Waste treatment is included where ever possible. When not possible the waste has been treated as an outflow not followed to the grave.

Geographical boundaries: The production of all Microsoft products take place at Shenzhen, China and Vietnam (Microsoft, 2020). The Microsoft HoloLens-2 is manufactured at Shenzhen, China. The products are then shipped to various parts of world for being used. In Europe, the arrival points are from China are Germany and Spain (Microsoft picks up two new HoloLens distributors in Europe - MSPoweruser, 2021). Sweden receives its HoloLens-2 from Germany through truck transportation. The End of Life of the electronics and materials used in the HoloLens-2 are either incinerated or sent to landfills are done in Sweden following the Swedish waste regulations.

Time horizon: The product use life is taken as 5 years. Though the devices can work even after 5 years, here we are considering the constant updates a device gets and thus the time of study is restricted five years.

4.1.5 Assumptions

The major assumption is made on the life time of the AR device. It is assumed that one device will be used for at least five years in the engine remanufacturing line unless it is economically and environmentally viable to change the device or any defect occurs to the device. A sensitivity analysis is also conducted to this assumptions and is presented in this thesis study.
An assumption is made that the shipping of Hololens from China to the final destination is a continuous process.

4.1.6 Limitations

HoloLens-2 primarily has materials like silicon, Acrylonitrile butadiene styrene(ABS) plastic, lithium, copper, glass, acrylics (Microsoft HoloLens — Design Life-Cycle, 2021). The amounts of these materials are not available in specifics as they are Microsoft products. So the inventory analysis and the impact assessment at the manufacturing level is restricted due to constraints.
While considering the energy use during the life cycle of the AR device, the energy used by the data servers and the cloud systems are unknown. The data for the complete energy use is not available and hence that makes the energy flow diagram incomplete. To study about the trend in the energy use by data servers, a study which compares performance of various data servers used United States is referred. Detailed explained of the results from the study is mentioned in section 4.2.3 under the use phase subsection.
The major limitation of the study is the unavailability of primary data as most of the data comes from secondary sources.

4.1.7 Actors

The main actors in this study are the Volvo organisation and the researchers at the University of Skövde who are involved in the implementation of Augmented Reality in the remanufacturing plat of Volvo GTO at Flen.

4.2 Inventory Analysis

The inventory analysis part can be divided into three parts, *Data collection, flow chart* and finally the *inventory results*. The data collection part consists of all the quantitative details of the inputs and outputs at each activity level of the LCA study. The flow chart depicts the energy flow and material flow from cradle to grave of the study. Finally, the inventory results present the normalised value of inputs and outputs in terms of the functional unit.

4.2.1 Data Collection

The data collection process begun with finding information of the components and the materials that are used in the Hololens-2. A lot of tear down videos and the Microsoft website gave a huge insight into the product details of the product. The table 2.1 shows that bill of materials of the product. The energy requirement, raw material at each independent activity/process is collected through the interviews with the researchers and professionals, who are specialised in the field of Augmented Reality and remanufacturing of engines. Furthermore, secondary literature was used to fill the gaps in data to complete the LCA study. The limitations of collecting the materials that are used in the manufacturing phase is mention in 4.1.6 limitations. Several sources were referred for the data collection. Some of the data was collected from the interviews with Volvo personal and the rest of the missing data was collected as secondary data from the literature. The various data sources used in the study is sorted and presented in the following table 4.1.

Life Stages	Data Source
Manufacturing of AR	(Wu et al., 2018) (Design Life-Cycle, 2021)
Shipping from China to Germany	(Corbett, 2003), (Eyring, 2005), (Sea route planner 2021)
Interstate transport from Germany to China	(Kodjak, Sharpe and Delgado, 2015, (Online HGV truck route planner for Europe, 2021), European reference life cycle database, Network for transport and the environment(NTM)
End of Life	Swedish Environmental Protection Agency, European reference life cycle database

Table 4.1: Summary of sources of Data

The following table 4.2 presents the emission values that are generated in manufacturing of HoloLens-2. The emissions are specified in terms of per kg of the HoloLens-2.

Chromium	4791 mg/Kg
Copper	72.25 mg/Kg
Zinc	123.8 mg/Kg
Arsenic	26.33 mg/Kg
Cadmium	4.03 mg/Kg
Nickel	51.92 mg/Kg
Lead	115mg/Kg

Table 4.2: Manufacturing Phase

There are two modes of transport that are considered in the entire life cycle of the device one being marine transport and the other one being truck transport. Ships are used to transport the devices from Shenzhen to Germany, where 22737km (A.1) is covered. Followed by this, a truck transport for the distance of 1300km (A.2) from Germany to Sweden is taken into consideration. The following tables 4.3 and 4.4 presents the emissions from both shipping and truck transportation.

Carbon dioxide	139.8 $gCO2/tkm$
Nitrous oxides	0.429 gNOx/tkm
Hydrocarbons	0.020 gHC/tkm
Particulate matter	0.0204 gPM/tkm
Carbon monoxide	0.0087 gCO/tkm
Sulphur dioxide	0.262 gSO2/tkm

Table 4.3: Shipping

Carbon dioxide	135.83 gCO2/tkm
Nitrous oxides	0.30 gNOx/tkm
Hydrocarbons	0.043 gHC/tkm
Particulate matter	0.0052 gPM/tkm
Carbon monoxide	0.041 gCO/tkm
Sulphur dioxide	0.01 gSO2/tkm

Table 4.4: Trucks

The use phase of the AR device is in the remanufacturing site at Volvo plant at Flen. There are no emissions in this stage as the emissions do not come under the scope of the study. The only consideration is the energy utilisation of the AR device at this stage.

Finally, the AR device is examined in its end of life, where all the electronic waste and other type of waste are handled in Sweden where metals are separated and finally sent either for landfills or incineration. Here landfills are accounted in terms of land use and incineration leads to release of certain emissions and the release of useful heat energy, which is presented in the following table. A truck transport from the plant to the incineration plants is estimated to be 30km (Recycling and disposal of electronic waste, 2011).

Carbon dioxide	2750 g/kg waste
Sulphur dioxide	0.2 g/kg waste
Hydrochloric acid	4.52 g/kg waste
Mercury	$5*10^{-5}$ g/kg waste
Carbon monoxide	3.17 g/kg waste
Polycyclic aromatic hydrocarbon (PAH)	$2.34*10^{-5}$ g/kg waste
Nitrous oxide	15 g/kg of waste
Methane	6.67 g/kg waste

Table 4.5: End of life - Incineration

Additional information was also collected from Volvo organisation regarding the remanufacturing process that is being carried out at the Flen plant. The key information that was gathered has been pointed as following,

1. Burning duration of engine companies at the burning station is approximately 6 hours and about 5-10 engines are burned per batch.
2. Diesel is used in the burning station.
3. The approximate time an engine is washed is 30 to 45 minutes.
4. The electricity consumption at the washing station is kWh/engine and water consumption are 50-75 lit/engine.
5. The average time for disassembling and assembling is 4-4,5 hours and 7-8 hours respectively.
6. The number of engines per day is 5 engines and 100 engines are remanufactured in a month.
7. It was suggested by Volvo to implemented AR in assembly and disassembly station as they are the most complicated and hard processes.

4.2.2 Flow Chart

With the system boundaries considered a flow diagram of all the relevant process/activities in the study is created and is presented in the figure. The flow chart, presented in figure 4.2 , can be divided into 3 segments: manufacturing of AR, Use-phase and End of life.

4.2.3 Inventory Results

The input materials and energy requirement at each process/activity are taken into consideration and normalised in terms of the functional unit of the study, which is per engine unit. The time horizon considered here for the study is 5 years, so the inputs and raw materials are normalised in terms of 5 years. From the acquired data, engine produced per month is 100 engines so the number of engines produced for a period of years is 6000 engines.

Manufacturing:

The raw materials used at the manufacturing phase are not known as mentioned in the limitations. The emissions are normalized in terms of the functional unit and are presented in the following table 4.6.

Chromium	0.452 mg/FU
Copper	0.007 mg/FU
Zinc	0.0292 mg/FU
Arsenic	0.006 mg/FU
Cadmium	0.0009 mg/FU
Nickel	0.012 mg/FU
Lead	0.027 mg/FU

Table 4.6: Inventory Analysis at Manufacturing Phase

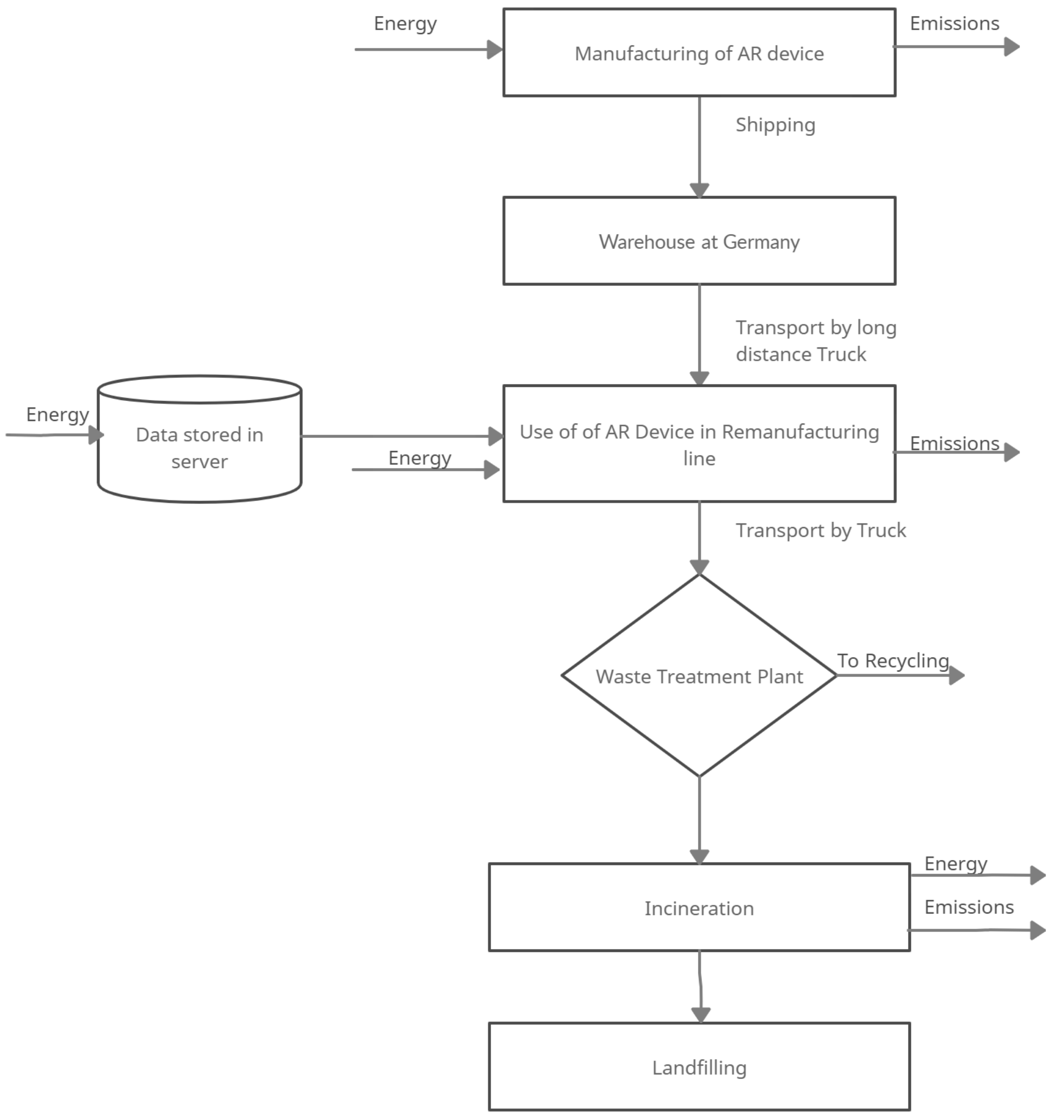


Figure 4.2: Flow Chart of the process flow considered in the LCA study

Use phase:

The HoloLens-2 are used in the remanufacturing plant.As mentioned earlier,AR will be used in the assembly and disassembly of the engine. Hence, the emissions from this phase is not considered in the scope of the study. The data used for this phase is directly obtained from the interviews conducted with the Volvo personal.This The energy used in remanufacturing one unit of engine is calculted as,

Assembly time = 7hours
Disassembly time = 4hours
Total time in use = 11hours
Battery Capacity = 16500mAh
No. of full charge required or one engine = 4
Energy use for one full charge = 99Wh
Total Energy used by AR = 0.099*4 = 0.4kWh/engine
Energy used during use phase without AR = 50kWh/engine
Total energy in use phase = 50.4kWh/engine

The energy used for the working of AR device also includes the energy used in the data servers and the energy used for the transfer of data and instructions to AR. As mentioned in the limitations earlier, specific data for this section was not available. According to Koomey et. al (2009), who studied the energy use and the performance of the data servers used commonly in the United States, points out the fact that the energy rating mentioned in the manufacturing details of the servers is not as same as the power consumed by the servers. It was also understood that the single unit servers use approximately 4333 Kwh/year in the United States during 2008. The live performance data of any server in Europe was not available and hence it is not considered here.

End of Life:

After the use phase, the device is sent to waste where the usable parts are reused/recycled in another device and the parts that cannot reused are sent to incineration and followed by land filling. The following table 4.7 represents the emissions during the end-of-life stage.

Carbon dioxide	0.259 mg/FU
Sulphur dioxide	$1.88*10^{-5}$ mg/FU
Hydrochloric acid	0.00043 mg/FU
Mercury	$4.72*10^{-9}$ mg/FU
Carbon monoxide	0.0003 mg/FU
Polycyclic aromatic hydrocarbon (PAH)	$2.21*10^{-9}$ mg/FU
Nitrous oxide	0.0014 mg/FU
Methane	0.00063 mg/FU

Table 4.7: End of life - Incineration

Transportation:

Here, the emissions in both modes of transportation, shipping and trucks, are analysed here. The fuel fuel used in the shipping process is heavy fuel oil and the fuel used in the two truck transportation's is diesel. The following tables 4.8, 4.9 and 4.10 present the inventory analysis of the transportation modes in the study.

Input: Heavy fuel oil	6847.928 mg/FU
Carbon dioxide	21673.69 mg/FU
Carbon monoxide	61.63 mg/FU
Nitrogen dioxide	575.227 mg/FU
Di-nitrogen monoxide	0.5483 mg/FU
Particulate matter (<10μm)	13.6967 mg/FU
Methane	0.55667 mg/FU
Sulphur dioxide	415.67 mg/FU
Non-methane Volatile Organic compounds	16.563 mg/FU

Table 4.8: Inventory analysis of Shipping

Input: Diesel	2.37 mg/FU
Carbon dioxide	7.51 mg/FU
Carbon monoxide	$1.07*10^{-2}$ mg/FU
Di-nitrogen monoxide	$5.81*10^{-5}$ mg/FU
Benzene	$5.15*10^{-5}$ mg/FU
Nitrogen dioxide	$6.33*10^{-2}$ mg/FU
Toluene	$9.87*10^{-6}$ mg/FU
Particulate matter (<2.5μm)	$1.22*10^{-3}$ mg/FU
Xylene	$2.47*10^{-5}$ mg/FU
Ammonia	$3.7*10^{-5}$ mg/FU
Sulphur dioxide	$2.36*10^{-4}$ mg/FU
Methane	$7.4*10^{-5}$ mg/FU
Non-methane Volatile Organic compounds	$2.92*10^{-3}$ mg/FU

Table 4.9: Inventory analysis of Trucks

Input: Diesel	0.19 mg/FU
Carbon dioxide	0.603333333 mg/FU
Carbon monoxide	0.001109138 mg/FU
Di-nitrogen monoxide	1.67*10^{-5} mg/FU
Benzene	5.15*10^{-5} mg/FU
Nitrogen dioxide	6.33*10^{-2} mg/FU
Toluene	9.87*10^{-6} mg/FU
Particulate matter (<2.5μm)	0.00012888 mg/FU
Xylene	3.075*10^{-6} mg/FU
Ammonia	8.913*10^{-6} mg/FU
Sulphur dioxide	1.8989*10^{-5} mg/FU
Methane	9.23*10^{-6} mg/FU
Non-methane Volatile Organic compounds	0.000364425 mg/FU

Table 4.10: Inventory analysis of Trucks-EOL

4.3 Life Cycle Impact Assessment

The LCIA is conducted with the help of OpenLCA software. Here all the data that was collected and the calculated data using inventory analysis were uploaded into the software the desired impact categories were analysed with the help of ReCiPe and CML database.

The assessments are presented two ways, one where each process in the life cycle are studied and a table representing a complete study of the impact of the life cycle of HoloLens-2 is studied. During the use-phase, there is no inputs or outputs that correspond to the scope of the study so the only the energy consumption is considered. Two sets of sensitivity analysis are also further discussed in this chapter.

4.3.1 Life Cycle Impact Assessment: Transport

The table 4.11 represents the impacts caused by the shipping process that is carried out in the life cycle. The tables 4.12 and 4.13 present the impact assessment results of the two truck transports that are considered in the study. Here the results are with respect to the functional unit of this LCA study.

Impact Category	Reference Unit	Results
Acidification potential - generic	kg SO_2 eq.	4.63*10^{-4}
Climate change - GWP100	kg CO_2 eq.	1.24*10^{-2}
Human toxicity - HTP100	kg 1,4-dichlorobenzene eq.	4.20*10^{-4}
Ozone layer depletion - ODP25	kg CFC-11 eq.	0
Photochemical oxidation - MOIR (high NOx)	kg formed ozone	1.01*10^{-6}

Table 4.11: Impact Assessment of the Shipping from China to Germany

Impact Category	Reference Unit	Results
Acidification potential - generic	kg SO_2 eq.	$2.52*10^{-8}$
Climate change - GWP100	kg CO_2 eq.	$4.26*10^{-6}$
Human toxicity - HTP100	kg 1,4-dichlorobenzene eq.	$9.89*10^{-8}$
Ozone layer depletion - ODP25	kg CFC-11 eq.	0
Photochemical oxidation - MOIR (high NOx)	kg formed ozone	$2.08*10^{-10}$

Table 4.12: Impact Assessment of Truck transport from Germany to Sweden

Impact Category	Reference Unit	Results
Acidification potential - generic	kg SO_2 eq.	$2.08*10^{-9}$
Climate change - GWP100	kg CO_2 eq.	$3.44*10^{-7}$
Human toxicity - HTP100	kg 1,4-dichlorobenzene eq.	$1.05*10^{-8}$
Ozone layer depletion - ODP25	kg CFC-11 eq.	0
Photochemical oxidation - MOIR (high NOx)	kg formed ozone	$2.23*10^{-11}$

Table 4.13: Impact Assessment of Truck transport to waste treatment

4.3.2 Life Cycle Impact Assessment: EoL

The tables 4.14 and 4.15 present the LCIA results that correspond to the end of life process that is incineration followed by landfilling here in this study. Here the results are with respect to the functional unit of this LCA study.

Impact Category	Reference Unit	Results
Acidification potential - generic	kg SO_2 eq.	$1.1983*10^{-6}$
Climate change - GWP100	kg CO_2 eq.	0.00010292
Human toxicity - HTP100	kg 1,4-dichlorobenzene eq.	$6.1025*10^{-6}$
Ozone layer depletion - ODP25	kg CFC-11 eq.	$9.30131*10^{-12}$
Photochemical oxidation - MOIR (high NOx)	kg formed ozone	$1.6896*10^{-8}$

Table 4.14: Impact Assessment of Incineration

Impact Category	Reference Unit	Results
Acidification potential - generic	kg SO_2 eq.	$2.29839*10^{-8}$
Climate change - GWP100	kg CO_2 eq.	$6.4776*10^{-6}$
Human toxicity - HTP100	kg 1,4-dichlorobenzene eq.	$1.2694*10^{-7}$
Ozone layer depletion - ODP25	kg CFC-11 eq.	$1.31614*10^{-13}$
Photochemical oxidation - MOIR (high NOx)	kg formed ozone	$1.6764*10^{-9}$

Table 4.15: Impact Assessment of Land-filling

4.3.3 Life Cycle Impact Assessment: Summary

The table 4.16 presents the whole summary of all processes involved the LCA study.

Impact Category	Reference Unit	Results
Acidification potential - generic	kg SO_2 eq.	$8.63*10^{-3}$
Climate change - GWP100	kg CO_2 eq.	0.0294
Human toxicity - HTP100	kg 1,4-dichlorobenzene eq.	0.001469
Ozone layer depletion - ODP25	kg CFC-11 eq.	$1.63*10^{-10}$
Photochemical oxidation - MOIR (high NOx)	kg formed ozone	$3.52*10^{-6}$

Table 4.16: Impact Assessment of the entire LCA Study

4.3.4 Sensitivity Analysis

There are two sensitivity analysis that are performed in this study. One which deals with the time horizon over which the study is carried and another analysis the mode of transport, shipping is replaced with railways to consider how this affects the environmental effects of the HoloLens-2.

Sensitivity Analysis-1: Time horizon

The study was carried with a data guarantee that the HoloLens-2 was guaranteed to work for 5 years. But there is always a chance of malfunction and constant upgrades that happen in the technological world, considering this variable we have chosen to consider a shorten time period of two years. The number of engines remanufactured over a period of 2 years and 5 years is 2400 engines and 6000 engines respectively. The following table 4.17 presents the LCIA results of both time horizon of 5 years and 2 years.

Impact Category	Reference Unit	2 years	5 years
Acidification potential - generic	kg SO_2 eq.	$2.16*10^{-3}$	$8.63*10^{-3}$
Climate change - GWP100	kg CO_2 eq.	0.073501	0.0294
Human toxicity - HTP100	kg 1,4-dichlorobenzene eq.	0.003672	0.001469
Ozone layer depletion - ODP25	kg CFC-11 eq.	$4.06*10^{-10}$	$1.63*10^{-10}$
Photochemical oxidation - MOIR (high NOx)	kg formed ozone	$8.8*10^{-6}$	$3.52*10^{-6}$

Table 4.17: Sensitivity Analysis-1: Time Horizon

Sensitivity Analysis-2: Mode of Transport

In this sensitivity analysis, the current shipping mode of transport is replaced with railways. A current project of connecting China with Europe is being discussed (ref). Considering this we have studied the environmental consequence using this mode pf transport. The following table 4.18 presents the LCIA study of using shipping and railways between China and Europe. Here the time horizon used is 5 years.

Impact Category	Reference Unit	Railways	Shipping
Acidification potential - generic	kg SO_2 eq.	$2.53*10^{-7}$	$4.63*10^{-4}$
Climate change - GWP100	kg CO_2 eq.	$2.16*10^{-5}$	$1.24*10^{-2}$
Human toxicity - HTP100	kg 1,4-dichlorobenzene eq.	$4.20*10^{-7}$	$4.20*10^{-4}$
Ozone layer depletion - ODP25	kg CFC-11 eq.	0	0
Photochemical oxidation - MOIR (high NOx)	kg formed ozone	$3.19*10^{-9}$	$1.01*10^{-6}$

Table 4.18: Sensitivity Analysis-2: Mode of Transport

4.3.5 Energy Usage

In this section, the energy consumed at each phase of the life cycle is calculated and presented in the table 4.19

Shipping:
The fuel used in the shipping process is heavy fuel oil . The amount of fuel used in the entire shipping process for transporting one unit of AR device is 41.087kg. With the calorific value of 40.44 MJ/kg the energy consumed is 461.54 kWh/AR device i.e., 0.076923333 kWh/FU.

Usephase:
The AR device is used in the assembly and disassembly phase of the remanufacturing line. The energy used during this phase is 50.4kWh/FU.

Internal transport from Germany to Sweden:
The fuel used in the trucks is diesel. The amount of diesel used in the entire shipping process for transporting one unit of AR device is 0.001419kg. With the calorific value of 42.96 MJ/kg the energy consumed is 0.1693 kWh/AR device,i.e., $2.82167*10^{-5}$ kWh/FU

Internal transport to Waste treatment:
The fuel used in the trucks is diesel. The amount of diesel used in the entire shipping process for transporting one unit of AR device is 0.00114kg. With the calorific value of 42.96 MJ/kg the energy consumed is 0.0136 kWh/AR device,i.e., $2.26667*10^{-6}$ kWh/FU.

Waste Incineration:
In waste incineration energy is recovered as a result of burning the waste. The energy recovered from incinerating waste is 1.52276 MJ or 0.4229kWh/AR device or 0.00007049 kWh/FU . This energy is considered as negative energy as it is recovered and used.

Stage	Results
Shipping	0.076923333 kWh/FU
Internal transport from Germany to Sweden	2.82167*10^{-5} kWh/FU
Internal transport to Waste treatment	2.26667*10^{-6} kWh/FU.
Waste Incineration (recovered)	-0.00007049 kWh/FU
Use Phase	50.4 kWh/FU

Table 4.19: Energy Usage

5

Discussions

With the impact assessment completed, the results of the impact assessment are discussed and presented here in this chapter. Graphs are used to depict the results. There are two types of analysis carried out while discussing the results *(i) Dominance Analysis, (ii) Contribution Analysis and (iii) Sensitivity Analysis.* All the results are in terms of the functional unit.

5.1 Dominance analysis

Here, the complete life cycle is compared against each other to see which impact has the highest impact among the impact categories. The figure 5.1 has the impact categories are along the X-axis and they are quantified against Y-axis. From the figure, it is clear climate change is the has the highest impact among the considered impact categories, i.e., the consequence of high global temperature is high as result of implementation of AR. Followed by climate change, the acidification potential is the next highest impact which is due to the high concentration of nitrogen oxides and sulphuric acids. The categories ozone layer depletion and photochemical oxidation categories have a negligible or very small impact in the overall environmental impacts.

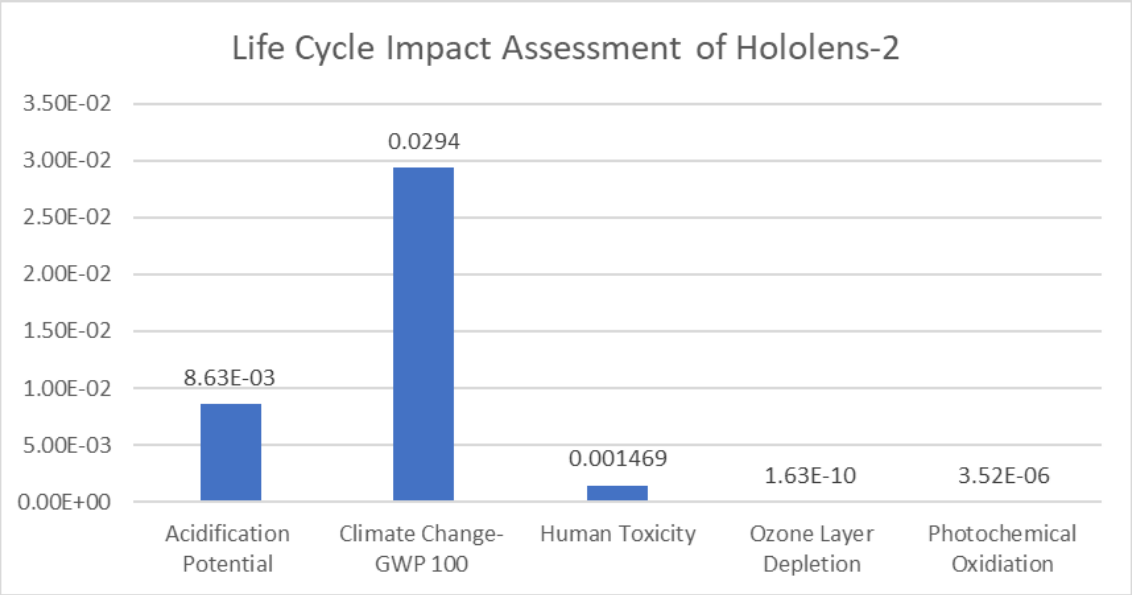


Figure 5.1: Dominance analysis

It can be seen from the inventory analysis that the carbon emissions are the dominating element in each stage of the life cycle of the AR device. this can be confirmed from the dominance analysis as the climate change, for which the carbon dioxide emissions are a major factor, is the dominating environmental impact among the ones considered.

In the following figure 5.2, the energy consumption and recovery that occurs during the life cycle of the Hololens-2 is depicted. From the figure it can be interpreted that the use phase of AR device accounts to the highest energy consuming stage, as the phase including the assembling and disassembling of the engine that is remanufactured. During the incineration process energy recovered and that is interpreted in terms of negative value. The units of the values in the figure are kWh/FU.

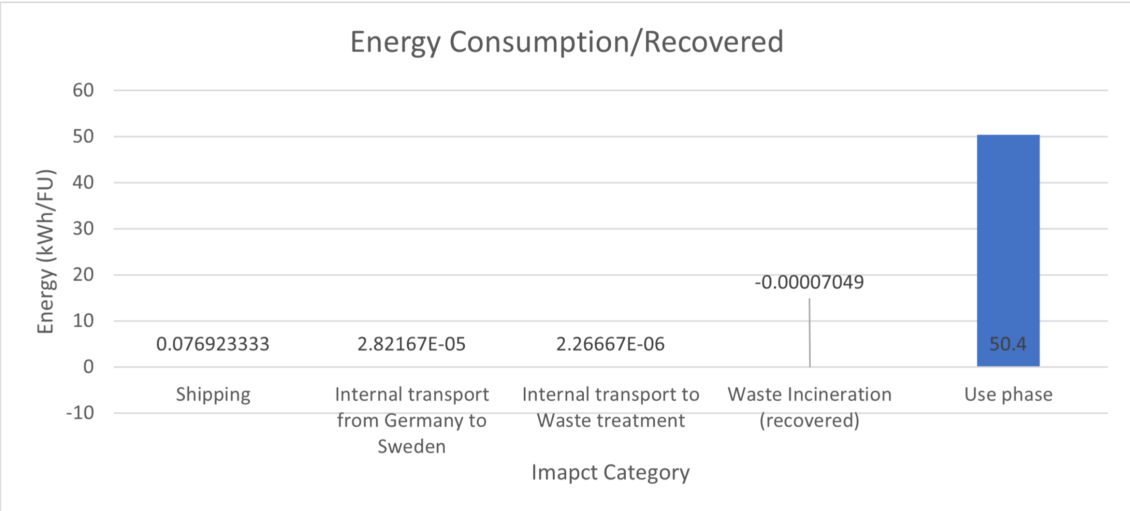


Figure 5.2: Energy Analysis

5.2 Contribution Analysis

In this analysis, how the different stages/phases in the life cycle study contribute to the various impact categories is analysed. The stages considered are the three transportation processes and the end of life of the device.

5.2.1 Acidification Potential

Here in this impact category, it is clear from the figure 5.3 that the shipping process contributes to majority of the acidification potential. The amount of sulphur is very high in marine fuels compared to road fuels, generating greater sulphur dioxide emissions. The mean sulphur content in the marine residual fuel is around 2.7% (European Environment Agency, 2013) compared to the allowed upper limit of 10ppm in road fuels. Sulphur dioxide emissions contribute to the formation of acid rain and adversely impacts human health (Harrison, 2001). A change of mode of transport can be help in reducing the environmental impact. Other stages have not registered significantly low values of acidification potential compared to hipping. the second highest contributor to acidification potential is incineration process. The units of the values in the figure are kg SO_2 eq/FU.

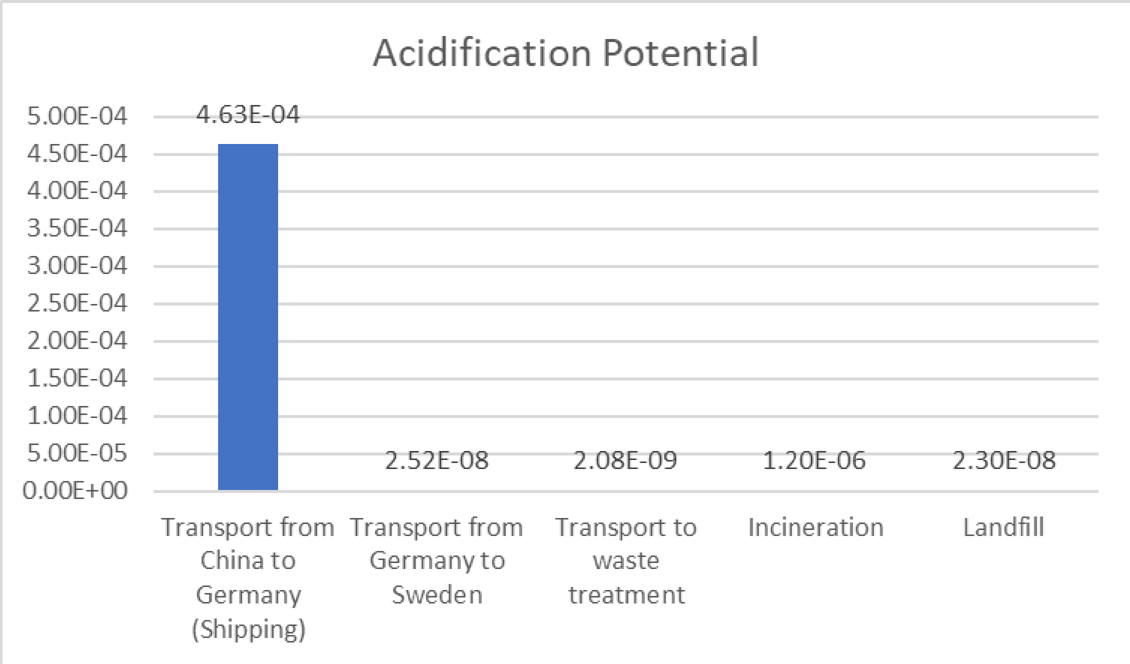


Figure 5.3: Contribution Analysis - Acidification Potential

5.2.2 Climate Change (GWP-100)

The global warming potential impact category corresponds to the global temperature increase or change because of certain gases like carbon dioxides being absorbed by the atmosphere and return act as green house. From the figure 5.4, shipping and incineration are the major processes that attribute to this impact category. Shipping again here is the highest contributor followed by incineration. The heavy fuel oil contribute to high amount of carbon dioxide and nitrogen oxides and thus resulting in high GWP values Spoof Tuomi and Niemi, (2020). The units of the values in the figure are kg CO_2 eq/FU.

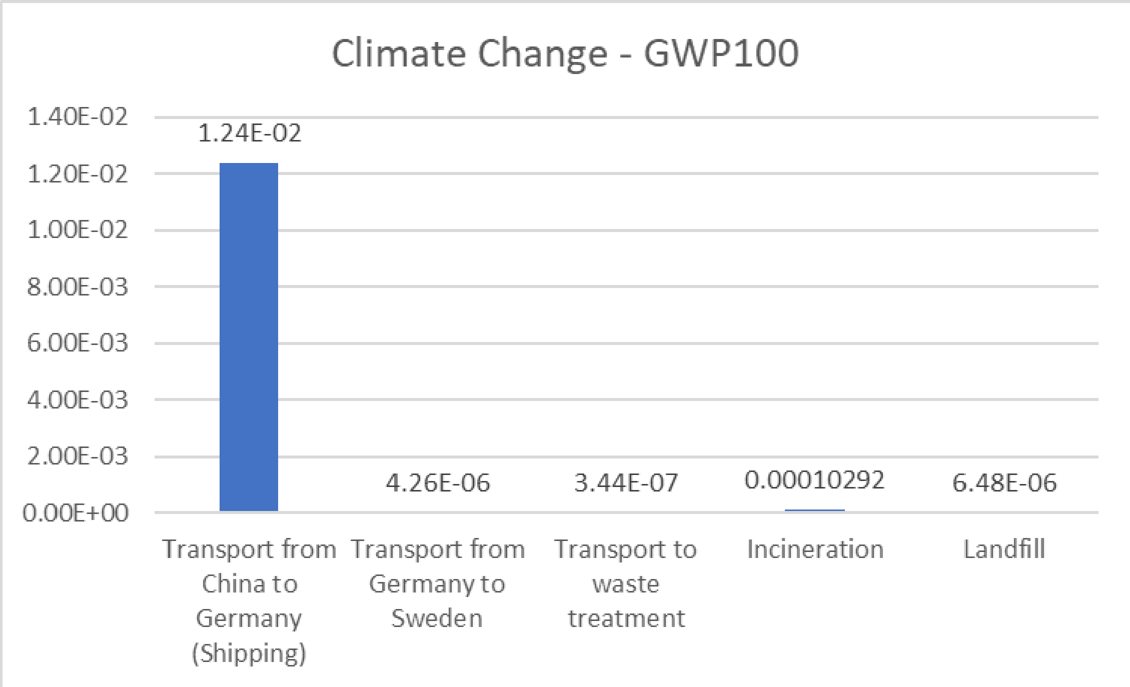


Figure 5.4: Contribution Analysis - Climate Change (GWP-100)

5.2.3 Human Toxicity

The figure 5.5 shows the contributions of each impact category and shows that the shipping is the highest contributor to human toxicity followed by incineration. The units of the values in the figure are kg 1,4-dichlorobenzene eq./FU.

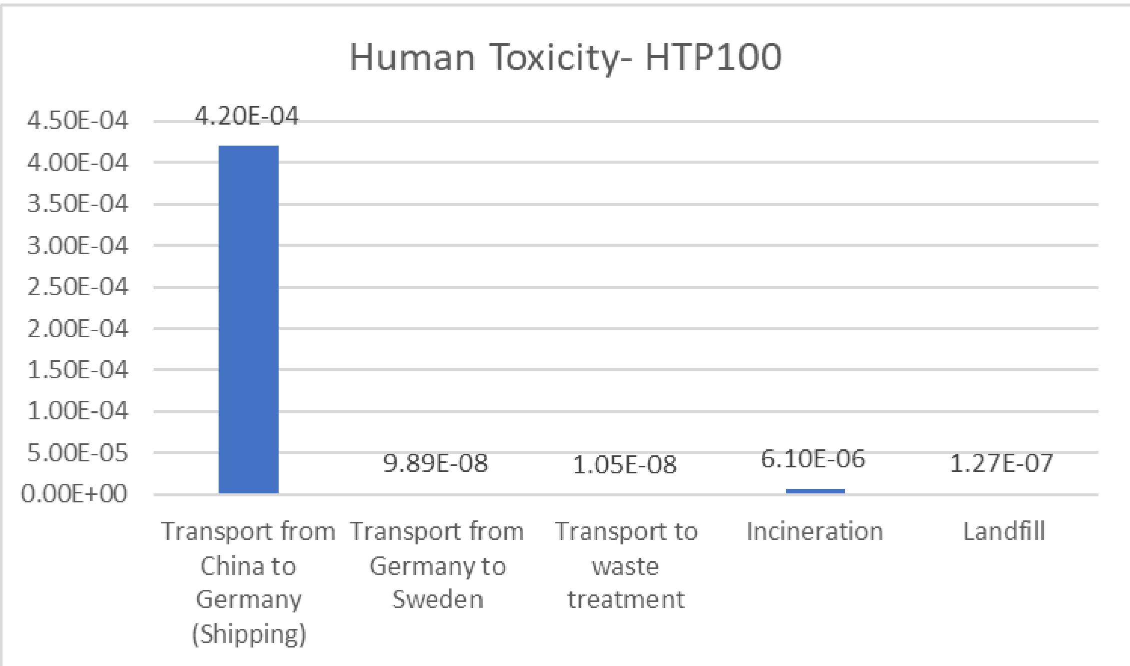


Figure 5.5: Contribution Analysis - Human Toxicity Potential

Like other impact factors, the human toxicity emissions are also the highest during the shipping stage of the AR device. During the burning of heavy oil fuels, particles such as Black carbon(BC), organic aerosols and some particulate matters are emitted to the atmosphere(Bilsback et al., 2020). The nitrogen oxides and the sulphur dioxide molecules released along with these aerosols react with matters in the atmosphere and turn into particle phase. These along with the primary particle emissions mentioned earlier comprises for the human toxicity factor of the shipping sector which causes 50,000 to 400,000 moralities per year(Bilsback et al., 2020).

5.2.4 Ozone Layer Depletion

This impact category corresponds to the gases that cause depletion of ozone layer in the stratosphere. From the figure 5.6, the incineration process contributes to this highest amount in this impact category followed by landfilling process. E- waste contributes to high concentration of ozone depletion due to the presence of harmful elements like mercury, lithium, plastics in printed circuit boards (Computer Disposal Limited, 2021). The units of the values in the figure are kg CFC-11 eq/FU.

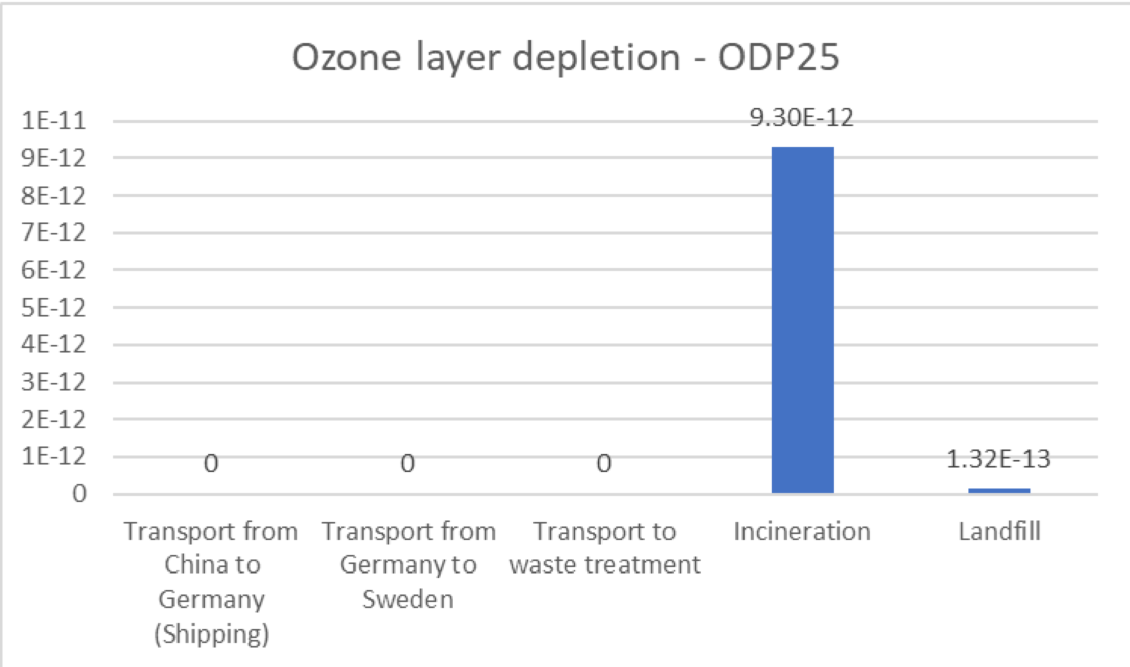


Figure 5.6: Contribution Analysis - Ozone Layer Depletion Potential

5.2.5 Photochemical Ozone Creation Potential

Following the trend in GWP-100, HTP-100 and acidification potential, shipping contributes to the highest impact in the photochemical oxidation category. The combustion process of HFO leads to release of nitrogen (Global Combustion Systems, 2021), which combines with oxygen to form nitrous oxides. Nitrous oxides causes the formation of photochemical ozone.Thus shipping contributes to high levels of POCP. The units of the values in the figure 5.7 are kg formed ozone/FU.

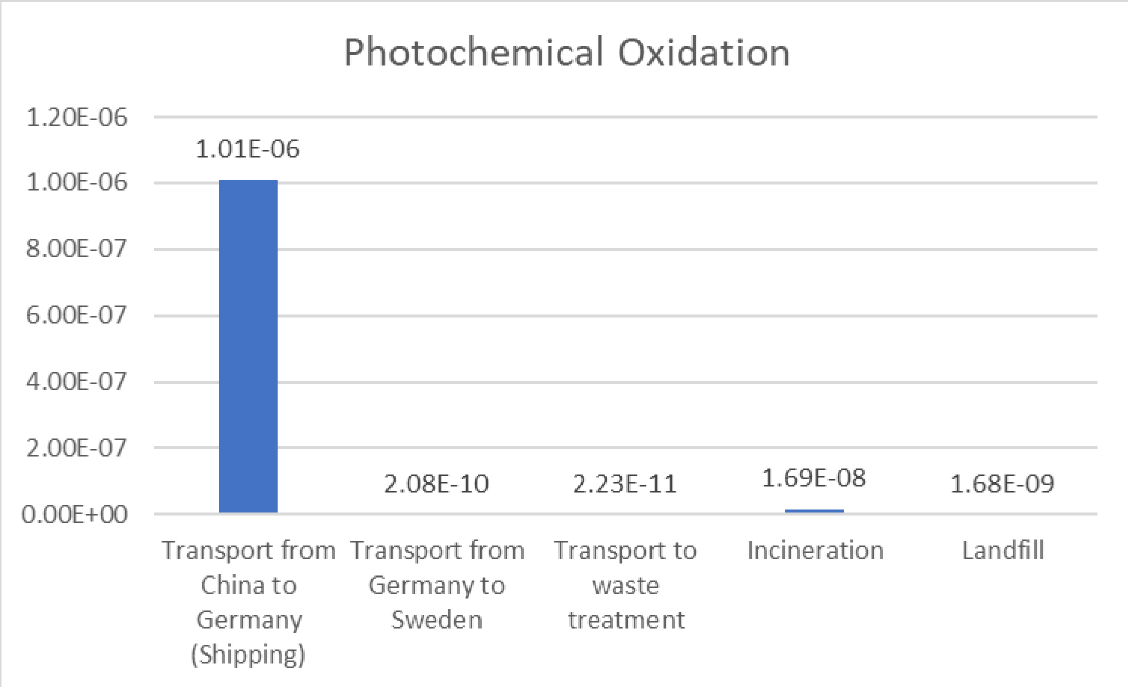


Figure 5.7: Contribution Analysis - Photochemical Oxidation Potential

In summary shipping is the hotspot for most of the impact categories and climate change biggest environmental impact that is climate change. The emissions from shipping of the device is high due to the fact that the shipping route is long and takes months to reach the destination. Due to this reason, a sensitivity analysis is done to check the reduction in the environmental impact when a direct railway line is used instead of the long shipping route. The calculations are explained in detail in the upcoming sections.

5.3 Sensitivity Analysis

In this section, the results from the two sensitivity analysis are discussed.

Sensitivity Analysis-1: Time horizon
The figure 5.8 gives a clear change in the impact categories. The categories ODP and Photochemical oxidation have no or very small change. The impact category GWP-100 has the biggest shift have the time period is reduced to 2 years and this is because all the emissions due to transport are so high that when accounted for 2 years than the previous 5 years. The acidification potential is reduced compared to 5 years as the concentrations of acids due to nitric acids and sulphuric acids are reduced due to the decreased time period. The human toxicity is has increased compared to the period of 5 years.

Sensitivity Analysis-2: Mode of Transport
From the figure 5.9 it can be confirmed that the use of railways over shipping will decrease the environmental impacts across all the five impact categories that are

considered in the study. This is mainly due to the reduced travel distance in railway transport than compared to shipping. the energy consumed in transporting per AR device in shipping is 461.54 kWh/AR device is reduced to 0.772kWh/AR device.

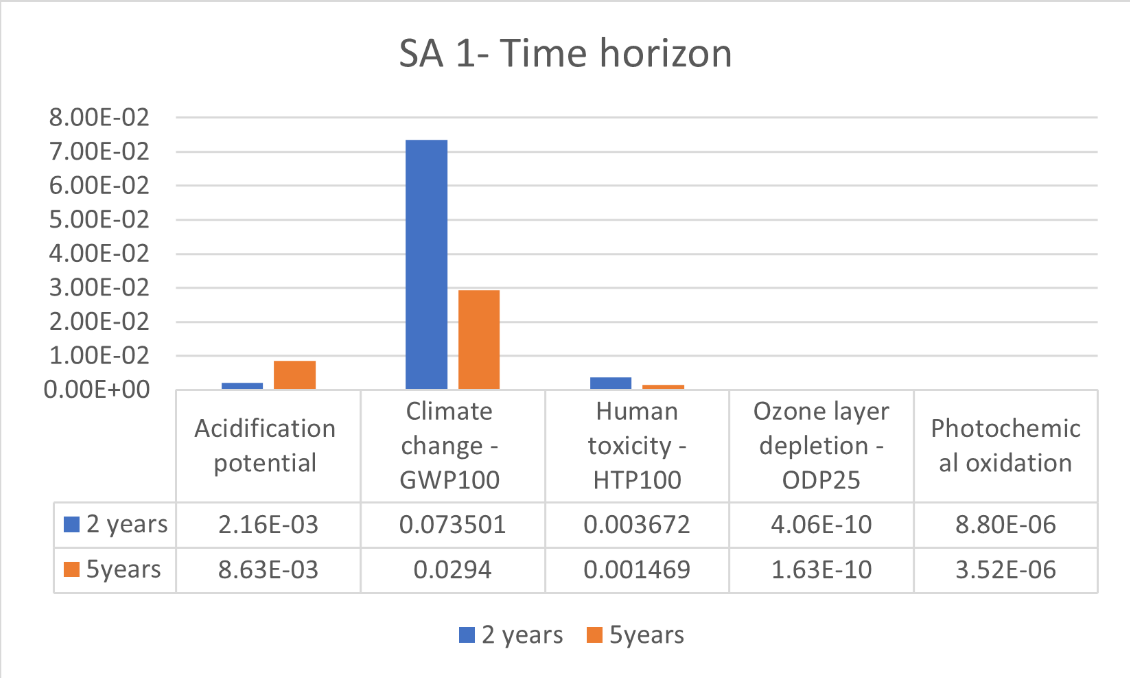


Figure 5.8: Sensitivity Analysis-1: Time horizon

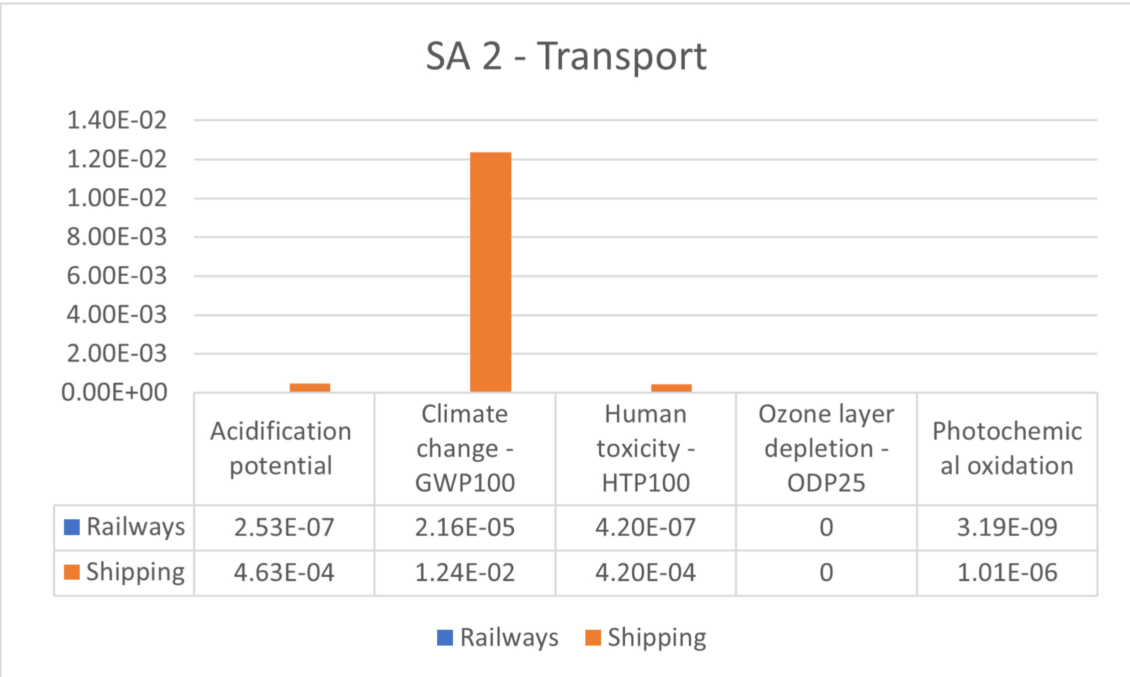


Figure 5.9: Sensitivity Analysis-2: Mode of Transport

6 Conclusion

The research question “What are the environmental impacts of the life cycle of AR devices implemented in the engine re-manufacturing process?” was answered with the help of the life cycle analysis in this method. A mixed approach of qualitative and quantitative approaches was of great aid to the background data and information that was required for the LCA method. This method has been suitable in quantifying all the emissions and categorising the pollutants.

From the study and the results, it can be found that the implementation of AR in the remanufacturing does have some impact on the environment. To check whether this impact is harmful for the environment or is it lesser than the impact created by the remanufacturing of the engine, a comparative study is to be done by comparing the environmental impacts of the remanufacturing process without the AR device and the impacts it has after the AR device has been implemented. The AR is believed by Volvo to reduce the lead time for the process and to eliminate some of the energy intended processes to an extend (like burning of the components to check whether they can be reused or should be sent to scrap). The current plan of Volvo is to implement the AR technology in the assembly and the disassembly of the engine, where they believe it can bring the biggest impact in terms of both reducing the lead time and increase economic benefits. As the process of implementing the AR is not completed and is still in the research phase, it cannot be concluded that the implementation can bring economic environmental or time benefits. But there are sufficient study to support that there are economic and time gains (Chang, Ong and Nee, 2017)

AR can be found useful in some other processes than assembly/disassembly such as quality control stations to reduce the lead time in these processes. But as there are a few studies on the implementation of the AR technology on the manufacturing processes, to what extend the implementation of the technology can benefit the manufacturing is yet to be known. A further study can be done after the implementation of the AR in the remanufacturing line on which of the processes the device can be beneficial, as the same AR device can be used to multiple purposes. Simple alteration in the calculations can be done in this study to incorporate more AR device and to evaluate the environmental impacts.

With the LCIA method, a wide range of analysis has been carried out to find the hotspots, where there are very heavy environmental loads, and have comparative study among then different phases of the life cycle and the different impact categories. From the LCA study, shipping process is the hotspot of environmental load in the whole study. The AR device in total has more impact on the Climate change than the other environmental indicators. The study is still not whole, as only 80% of the data has been considered in this project and the remaining data in the manufacturing phase of AR is disregarded due to the limitations mentioned. Introducing this variable can change the distribution of environmental loads but still the transport sector will hold a large part of the impact (International Energy Agency, 2020).

The simulation done using the OpenLCA software in this study can be used for testing different parameters such as, assessing the environmental impacts by an AR device that is manufactured inside Europe, to assess the environmental impact if the productivity of the remanufacturing plant is increased, for any alternative ways of transport etc. As the calculation is done separately for different stages in the life cycle of the AR device, any change in the parameters can be easily done in the calculations. This study can be used for the further research on different kinds of AR devices and different manufacturing processes by changing the weightage of the parameters used for the calculation in the study.

A future study of comparative study can be made to see environmental benefits of implementing AR in an industry by caring out a LCA study before implementing and after implementing and compare the results. The implementation of NOx and Sox filters can be used in the ships to decrease the impact of acidification and photochemical ozone formation (Bengtsson, 2011). The LCIA study supports the current debate of changing to alternative shipping fuels based on natural gases. These fuels have reduced the impacts of GWP, acidification and POCP drastically (Brynolf, 2014). Policies can be implemented to bring the price of these alternative fuels competitive with the already existing crude-oil based fuels. Also Brynolf (2015), shown that the use of alternative synthetic fuels has decreased the impact of GWP-100.

Bibliography

Abokyi, E., Appiah-Konadu, P., Abokyi, F. and Oteng-Abayie, E., 2019. Industrial growth and emissions of CO2 in Ghana: The role of financial development and fossil fuel consumption. Energy Reports, 5, pp.1339-1353.

Acero, A., Rodríguez, C. and Ciroth, A., 2017. LCIA methods - Impact assessment methods in Life Cycle Assessment and their impact categories., Green Delta.

Adler, D., Ludewig, P., Kumar, V. and Sutherland, J., 2007. Comparing Energy and Other Measures of Environmental Performance in the Original Manufacturing and Remanufacturing of Engine Components. ASME 2007 International Manufacturing Science and Engineering Conference.

Alipour, S. and Galal Ahmed, K., 2021. Assessing the effect of urban form on social sustainability: a proposed 'Integrated Measuring Tools Method' for urban neighborhoods in Dubai. City, Territory and Architecture, 8(1).

Azuma, R., 1997. A Survey of Augmented Reality. Presence: Teleoperators and Virtual Environments, 6(4), pp.355-385.

Batth, R., Nayyar, A. and Nagpal, A., 2018. Internet of Robotic Things: Driving Intelligent Robotics of Future - Concept, Architecture, Applications and Technologies. 2018 4th International Conference on Computing Sciences (ICCS),.

Baumann, H. and Tillman, A., 2004. The hitchhiker's guide to LCA. Lund: Studentlitteratur.

Berryman, D., 2012. Augmented Reality: A Review. Medical Reference Services Quarterly, 31(2), pp.212-218.

Bengtsson, S., 2011. Life Cycle Assessment of Present and Future Marine Fuels. Chalmers Library Print Collection.

Bilsback, K., Kerry, D., Croft, B., Ford, B., Jathar, S., Carter, E., Martin, R. and Pierce, J., 2020. Beyond SOx reductions from shipping: assessing the impact of NOx and carbonaceous-particle controls on human health and climate. Environmental Research Letters, 15(12), p.124046.

Bottani, E. and Vignali, G., 2019. Augmented reality technology in the manufacturing industry: A review of the last decade. IISE Transactions, 51(3), pp.284-310.

Brundtland, G.H., Khalid, M., Agnelli, S., Al-Athel, S. and Chidzero, B.J.N.Y., 1987. Our common future. New York, 8.

Brynolf, S., 2014. Environmental assessment of present and future marine fuels. Chalmers Library Print Collection.

Chang, M., Ong, S. and Nee, A., 2017. AR-guided Product Disassembly for Maintenance and Remanufacturing. Procedia CIRP, 61, pp.299-304.

Climateanalytics.org. 2021. Why using 20-year Global Warming Potentials (GWPs) for emission targets are a very bad idea for climate policy. [online] Available at: <https://climateanalytics.org/publications/2017/why-using-20-year-global-warming-potentials-gwps-for-emission-targets-are-a-very-bad-idea-for-climate-policy/> [Accessed 15 May 2021].

Computer Disposal Limited. 2021. E-waste. Just a mountain of rubbish? Or a dangerous ozone depletor? - Computer Disposal Limited. [online] Available at: <https://www.computerdisposals.com/blog/e-waste-just-a-mountain-of-rubbish-or-a-dangerous-ozone-depletor/> [Accessed 1 June 2021].

Corbett, J., 2003. Updated emissions from ocean shipping. Journal of Geophysical Research, 108(D20).

Design Life-Cycle. 2021. Microsoft HoloLens — Design Life-Cycle. [online] Available at: <http://www.designlife-cycle.com/microsoft-hololens?rq=hololens> [Accessed 6 April 2021].

Docs.microsoft.com. 2021. HoloLens 2 hardware. [online] Available at: <https://docs.microsoft.com/en-us/hololens/hololens2-hardware#sensors> [Accessed 22 May 2021].

Enyoghasi, C. and Badurdeen, F., 2021. Industry 4.0 for sustainable manufacturing: Opportunities at the product, process, and system levels. Resources, Conservation and Recycling, 166, p.105362.

European Environment Agency, 2013. The impact of international shipping on European air quality and climate forcing, Copenhagen.

Eyring, V., 2005. Emissions from international shipping: 1. The last 50 years. Journal of Geophysical Research, 110(D17).

Fettermann, D., Cavalcante, C., Almeida, T. and Tortorella, G., 2018. How does Industry 4.0 contribute to operations management?. Journal of Industrial and Production Engineering, 35(4), pp.255-268.

Harrison, R.M., 2001. Pollution: causes, effects and control. Royal Society of Chemistry, Cambridge.

Hobson, K., 2020. The limits of the loops: critical environmental politics and the Circular Economy. Environmental Politics, 30(1-2), pp.161-179.

IPCS, C., 2021. Explanation of Augmented Reality (AR) - Application & Classification. [online] IPCS Automation. Available at: <https://ipcsautomation.com/blog-post/explanation-of-augmented-reality-ar-application-classification/> [Accessed 3 April 2021].

IEA (2020), Tracking Industry 2020, IEA, Paris https://www.iea.org/reports/tracking-industry-2020.

Impargo.de. 2021. Online HGV truck route planner for Europe. [online] [Accessed 15 June 2021].

ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework.

ISO 14044:2006, Environmental management — Life cycle assessment — Requirements and guidelines.

Jayal, A., Badurdeen, F., Dillon, O. and Jawahir, I., 2010. Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP Journal of Manufacturing Science and Technology, 2(3), pp.144-152.

Jun, Y., Kang, H., Jo, H., Baek, C. and Kim, Y., 2019. Evaluation of environmental impact and benefits for remanufactured construction equipment parts using Life Cycle Assessment. Procedia Manufacturing, 33, pp.288-295.

Kerin, M. and Pham, D., 2019. A review of emerging industry 4.0 technologies in remanufacturing. Journal of Cleaner Production, 237, p.117805.

Kodjak, D., Sharpe, B. and Delgado, O., 2015. Evolution of heavy-duty vehicle fuel efficiency policies in major markets. Mitigation and Adaptation Strategies for Global Change, 20(5), pp.755-775.

Koomey, J.G., Belady, C., Patterson, M., Santos, A. and Lange, K.D., 2009. Assessing trends over time in performance, costs, and energy use for servers. Lawrence Berkeley National Laboratory, Stanford University, Microsoft Corporation, and Intel Corporation, Tech. Rep.

Lavingia, K. and Tanwar, S., 2019. Augmented Reality and Industry 4.0. A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development, pp.143-155.

Liu, Z., Li, T., Jiang, Q. and Zhang, H., 2014. Life Cycle Assessment-based Comparative Evaluation of Originally Manufactured and Remanufactured Diesel Engines. Journal of Industrial Ecology, 18(4), pp.567-576.

MacArthur, E., 2013. Towards the circular economy. Journal of Industrial Ecology, 2, pp.23-44.

Microsoft Corporation,2020. Form 10-K. [online] Washington DC: SECURITIES AND EXCHANGE COMMISSION.

Microsoft.com. 2021. Microsoft HoloLens | Mixed Reality Technology forBusiness. [online] Available at: <https://www.microsoft.com/en-gb/hololens> [Ac-cessed 16 May 2021]

MSPoweruser. 2021. Microsoft picks up two new HoloLens distributors in Europe - MSPoweruser. [online] Available at: <https://mspoweruser.com/microsoft-picks-two-new-hololens-distributors-europe/> [Accessed 29 May 2021].

Openlca.org. 2021. [online] Available at: <https://www.openlca.org/wp-content/uploads/2015/11/screen.png> [Accessed 22 May 2021].

Ports.com. 2021. Port of Shanghai, China to Port of Hamburg, Germany sea route and distance. [online] Available at: <http://ports.com/sea-route/port-of-shanghai,china/port-of-hamburg,germany/> [Accessed 15 June 2021].

Recycling and disposal of electronc waste,2011. Stockholm:Naturvårdsverket

Schroeder, P., Anggraeni, K. and Weber, U., 2018. The Relevance of Circular Economy Practices to the Sustainable Development Goals. Journal of Industrial Ecology, 23(1), pp.77-95.

Silva, Diogo & Nunes, Andréa & Piekarski, Cassiano & Moris, Virgínia & Souza, Luri & Rodrigues, Thiago. (2019). Why using different Life Cycle Assessment software tools can generate different results for the same product system? A cause–effect analysis of the problem. 20. 304-315. 10.1016/j.spc.2019.07.005.

Spoof-Tuomi, K. & Niemi, S., 2020. Environmental and Economic Evaluation of Fuel Choices for Short Sea Shipping. Clean Technologies, 2(1), pp.34–52. Available at: http://dx.doi.org/10.3390/cleantechnol2010004.

Sustainabledevelopment.un.org. 2021. Transforming our World: The 2030 Agenda for Sustainable Development. [online] Available at: <https://sustainabledevelopment.un.org/post2015/transformingourworld/publication> [Accessed 25 May 2021].

Wu, W., Wu, P., Yang, F., Sun, D., Zhang, D. and Zhou, Y., 2018. Assessment of heavy metal pollution and human health risks in urban soils around an electronics manufacturing facility. Science of The Total Environment, 630, pp.53-61.

Yin, R., 2009. Case study research. Thousand Oaks: Sage.

Zheng, H., Li, E., Wang, Y., Shi, P., Xu, B. and Yang, S., 2019. Environmental life cycle assessment of remanufactured engines with advanced restoring technologies. Robotics and Computer-Integrated Manufacturing, 59, pp.213-221.

A
Appendix 1

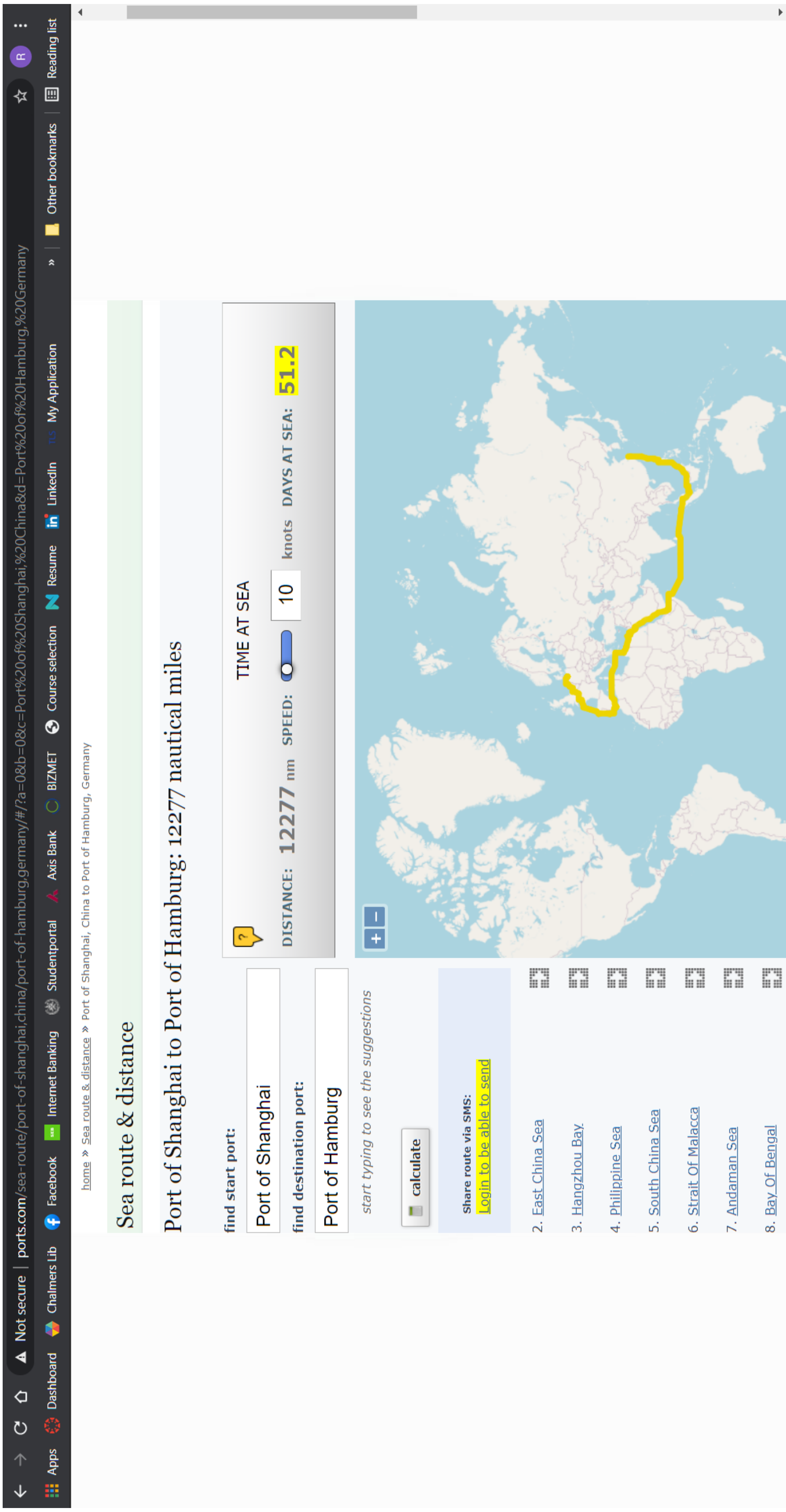


Figure A.1: Route planner for the shipping route from China to Germany

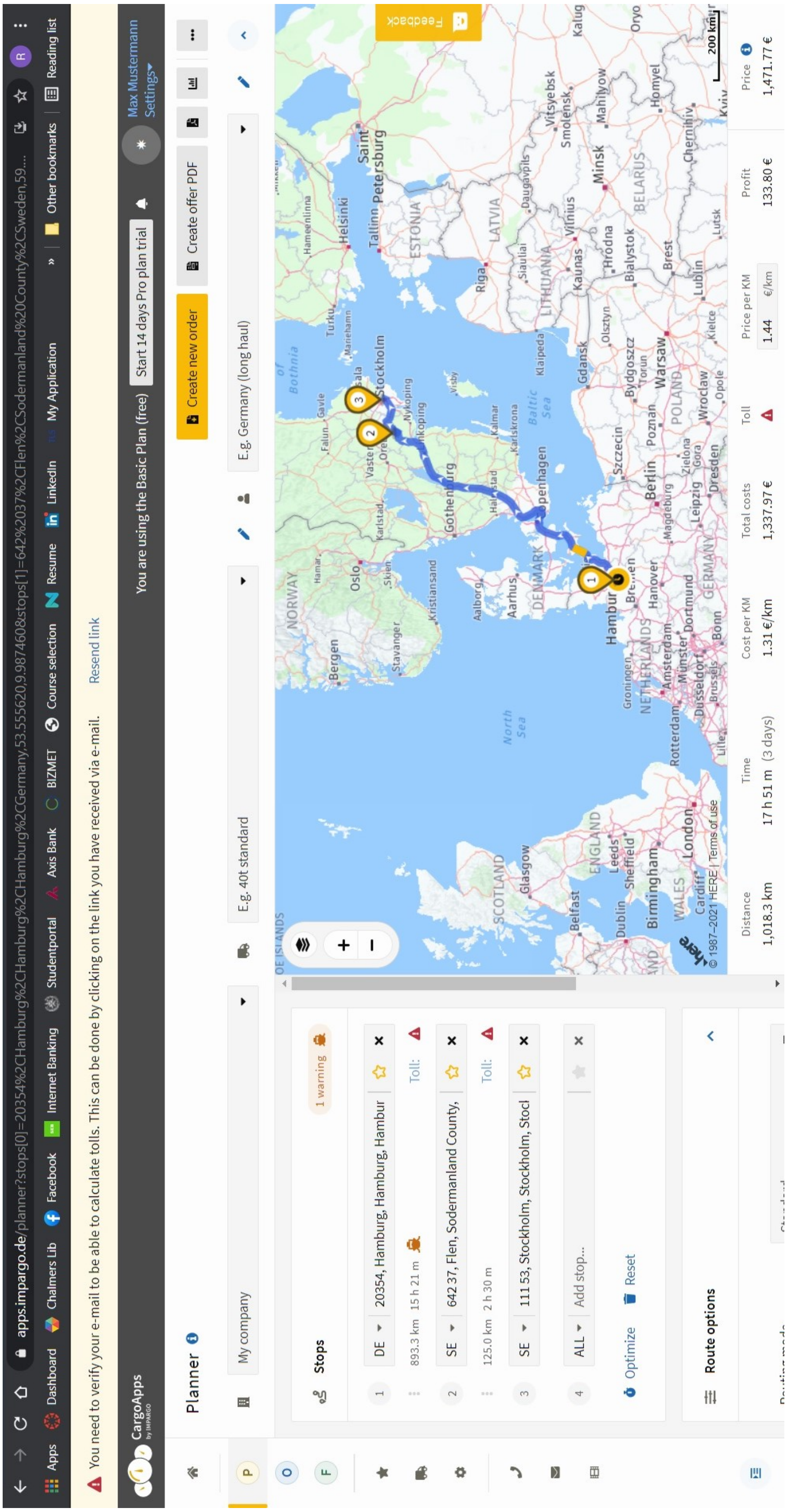
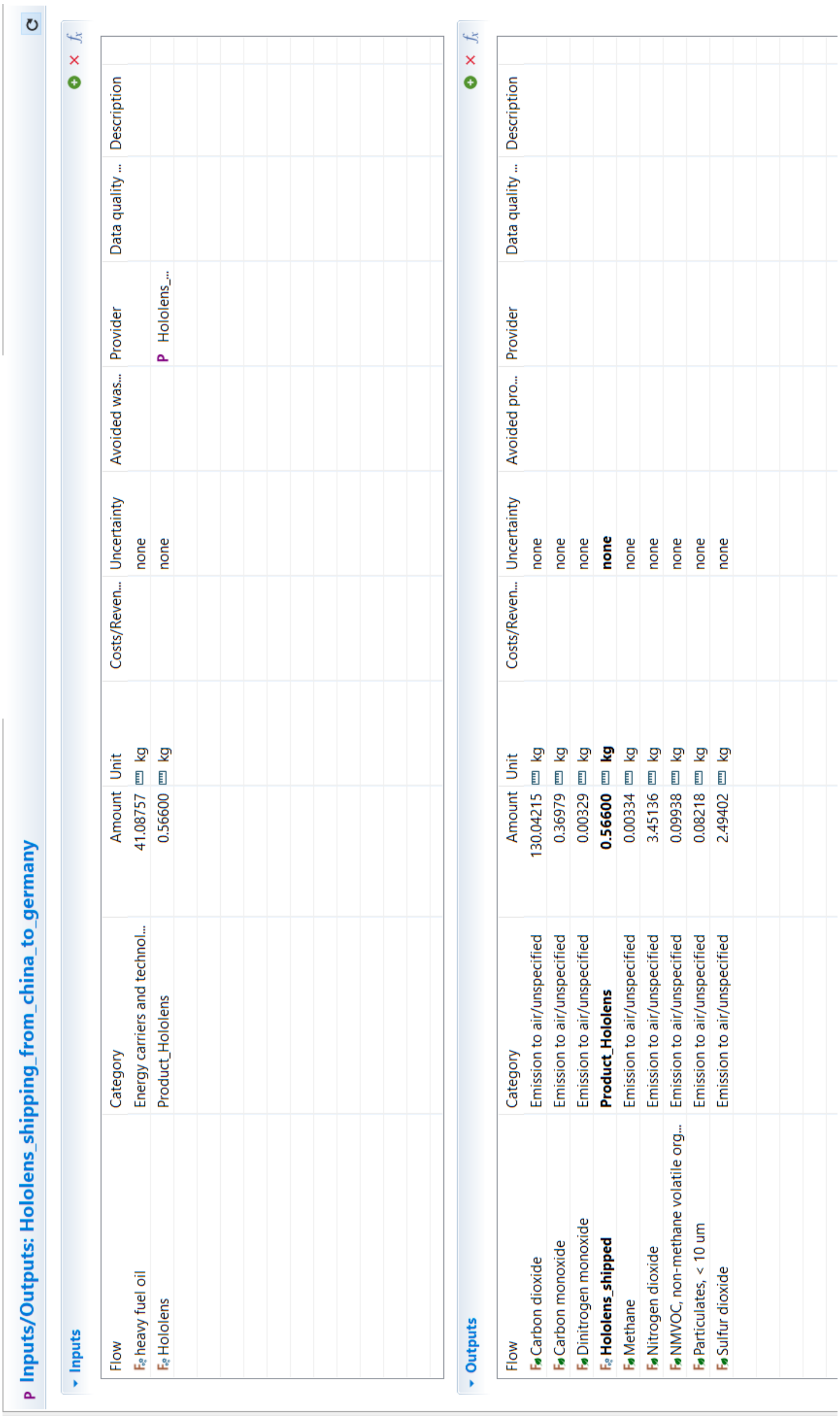


Figure A.2: Route planner for truck routes from Germany to the Volvo factory in Flen, Sweden



Inputs/Outputs: Hololens_shipping_from_china_to_germany

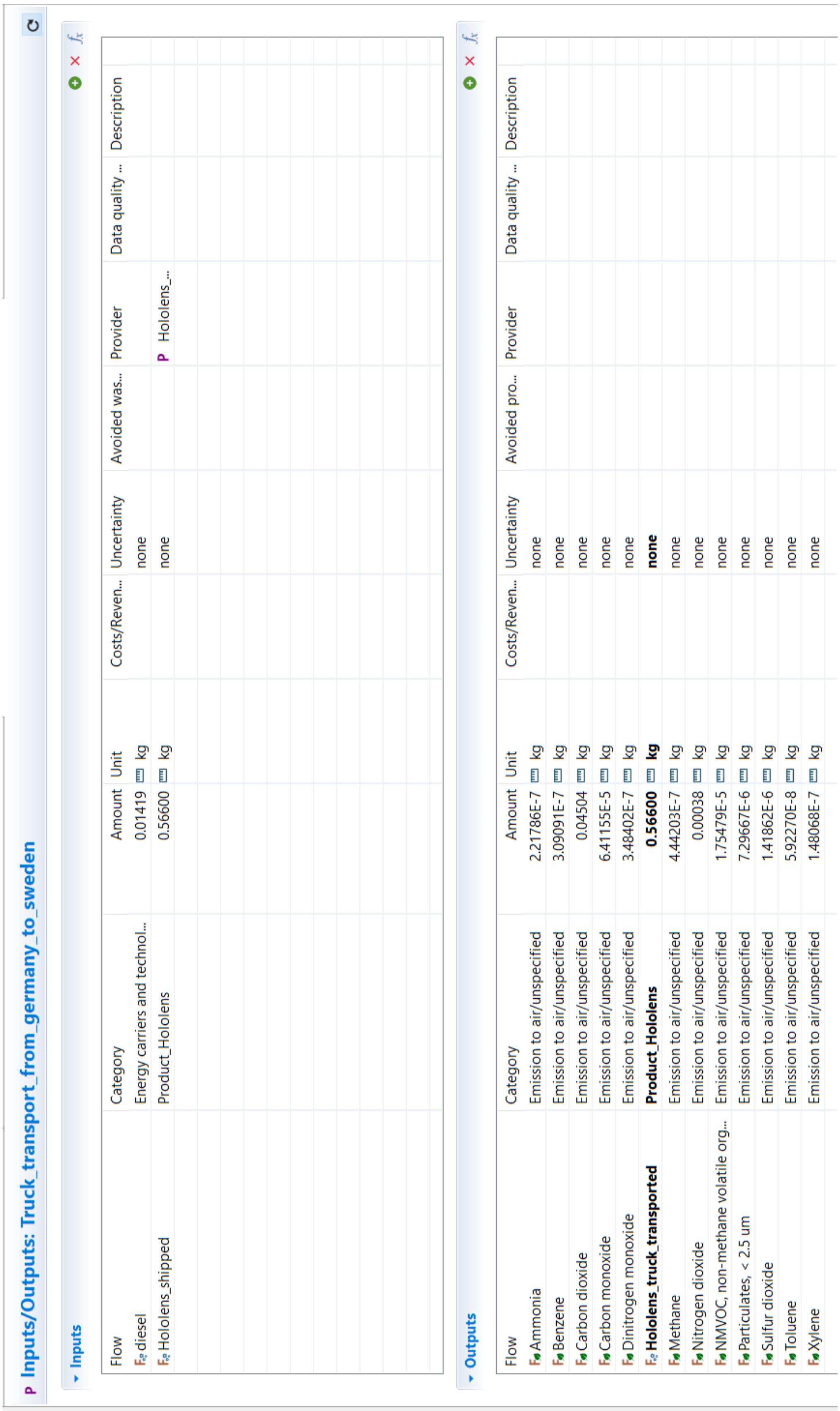
Inputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided was...	Provider	Data quality ...	Description
heavy fuel oil	Energy carriers and technol...	41.08757	kg		none				
Hololens	Product_Hololens	0.56600	kg		none		Hololens_...		

Outputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided pro...	Provider	Data quality ...	Description
Carbon dioxide	Emission to air/unspecified	130.04215	kg		none				
Carbon monoxide	Emission to air/unspecified	0.36979	kg		none				
Dinitrogen monoxide	Emission to air/unspecified	0.00329	kg		none				
Hololens_shipped	**Product_Hololens**	**0.56600**	**kg**		**none**				
Methane	Emission to air/unspecified	0.00334	kg		none				
Nitrogen dioxide	Emission to air/unspecified	3.45136	kg		none				
NMVOC, non-methane volatile org...	Emission to air/unspecified	0.09938	kg		none				
Particulates, < 10 um	Emission to air/unspecified	0.08218	kg		none				
Sulfur dioxide	Emission to air/unspecified	2.49402	kg		none				

Figure A.3: Input and Output flows in the Shipping stage



Inputs/Outputs: Truck_transport_from_germany_to_sweden

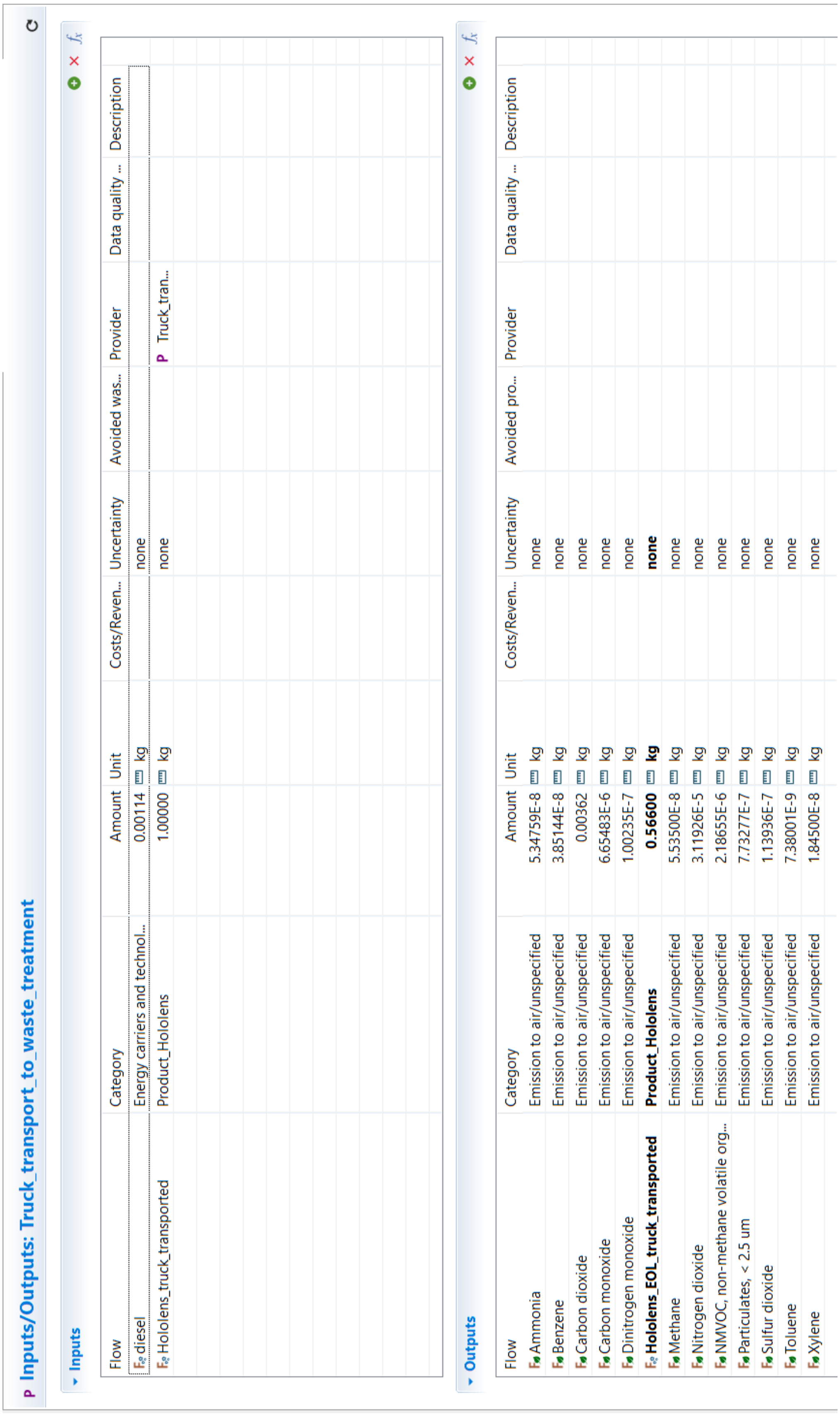
Inputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided was...	Provider	Data quality ...	Description
diesel	Energy carriers and technol...	0.01419	kg		none				
Hololens_shipped	Product_Hololens	0.56600	kg		none		Hololens_...		

Outputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided pro...	Provider	Data quality ...	Description
Ammonia	Emission to air/unspecified	2.21786E-7	kg		none				
Benzene	Emission to air/unspecified	3.09091E-7	kg		none				
Carbon dioxide	Emission to air/unspecified	0.04504	kg		none				
Carbon monoxide	Emission to air/unspecified	6.41155E-5	kg		none				
Dinitrogen monoxide	Emission to air/unspecified	3.48402E-7	kg		none				
Hololens_truck_transported	**Product_Hololens**	**0.56600**	**kg**		**none**				
Methane	Emission to air/unspecified	4.44203E-7	kg		none				
Nitrogen dioxide	Emission to air/unspecified	0.00038	kg		none				
NMVOC, non-methane volatile org...	Emission to air/unspecified	1.75479E-5	kg		none				
Particulates, < 2.5 um	Emission to air/unspecified	7.29667E-6	kg		none				
Sulfur dioxide	Emission to air/unspecified	1.41862E-6	kg		none				
Toluene	Emission to air/unspecified	5.92270E-8	kg		none				
Xylene	Emission to air/unspecified	1.48068E-7	kg		none				

Figure A.4: Input and Output flows in the Truck transport from Germany to Sweden



Inputs/Outputs: Truck_transport_to_waste_treatment

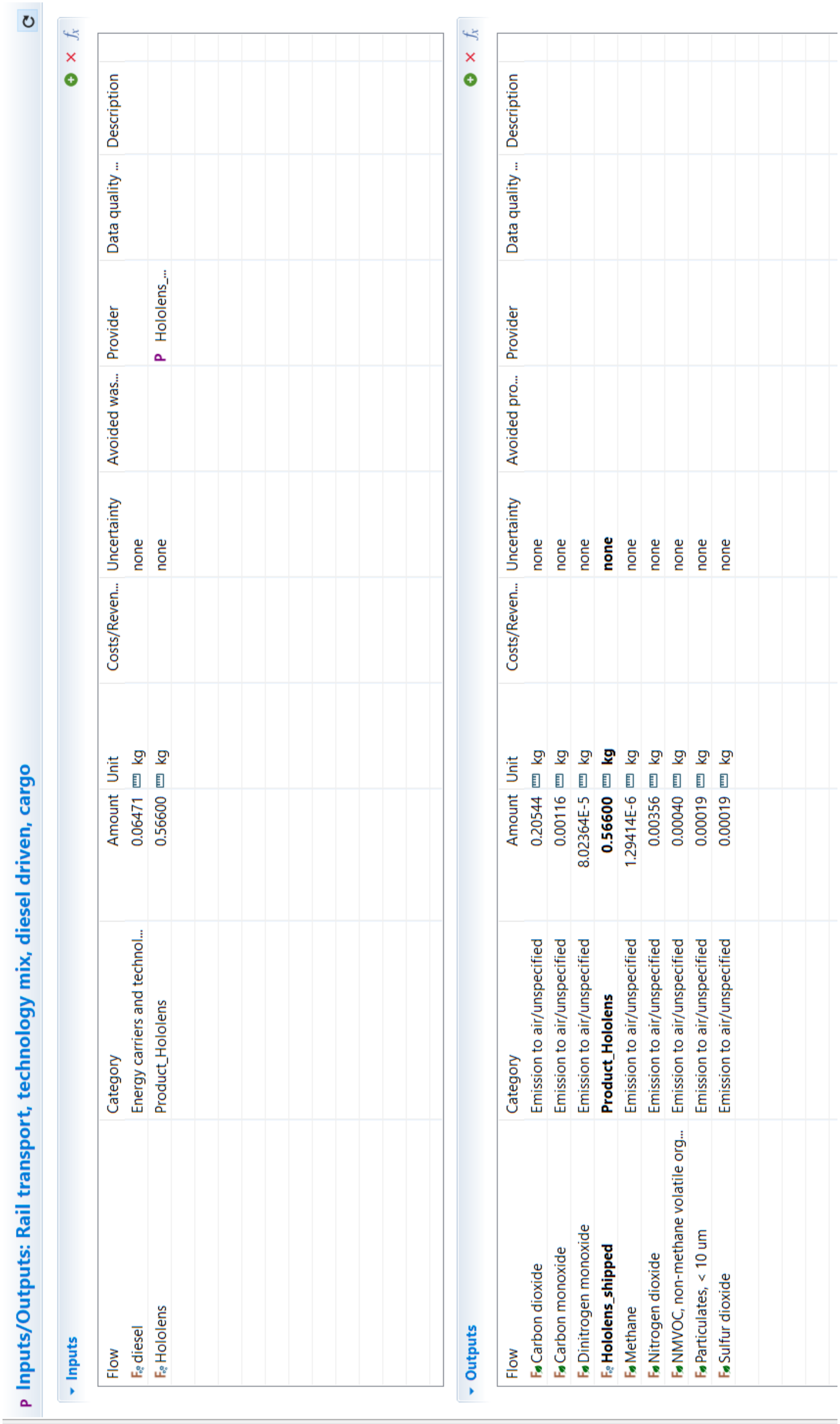
Inputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided was...	Provider	Data quality ...	Description
diesel	Energy carriers and technol...	0.00114	kg		none				
Hololens_truck_transported	Product_Hololens	1.00000	kg		none		Truck_tran...		

Outputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided pro...	Provider	Data quality ...	Description
Ammonia	Emission to air/unspecified	5.34759E-8	kg		none				
Benzene	Emission to air/unspecified	3.85144E-8	kg		none				
Carbon dioxide	Emission to air/unspecified	0.00362	kg		none				
Carbon monoxide	Emission to air/unspecified	6.65483E-6	kg		none				
Dinitrogen monoxide	Emission to air/unspecified	1.00235E-7	kg		none				
Hololens_EOL_truck_transported	**Product_Hololens**	**0.56600**	**kg**		**none**				
Methane	Emission to air/unspecified	5.53500E-8	kg		none				
Nitrogen dioxide	Emission to air/unspecified	3.11926E-5	kg		none				
NMVOC, non-methane volatile org...	Emission to air/unspecified	2.18655E-6	kg		none				
Particulates, < 2.5 um	Emission to air/unspecified	7.73277E-7	kg		none				
Sulfur dioxide	Emission to air/unspecified	1.13936E-7	kg		none				
Toluene	Emission to air/unspecified	7.38001E-9	kg		none				
Xylene	Emission to air/unspecified	1.84500E-8	kg		none				

Figure A.5: Input and Output flows in the transportation of the AR device to the Waste treatment plant



Inputs/Outputs: Rail transport, technology mix, diesel driven, cargo

Inputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided was...	Provider	Data quality ...	Description
diesel	Energy carriers and technol...	0.06471	kg		none				
Hololens	Product_Hololens	0.56600	kg		none		Hololens_...		

Outputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided pro...	Provider	Data quality ...	Description
Carbon dioxide	Emission to air/unspecified	0.20544	kg		none				
Carbon monoxide	Emission to air/unspecified	0.00116	kg		none				
Dinitrogen monoxide	Emission to air/unspecified	8.02364E-5	kg		none				
Hololens_shipped	**Product_Hololens**	**0.56600**	**kg**		**none**				
Methane	Emission to air/unspecified	1.29414E-6	kg		none				
Nitrogen dioxide	Emission to air/unspecified	0.00356	kg		none				
NMVOC, non-methane volatile org...	Emission to air/unspecified	0.00040	kg		none				
Particulates, < 10 um	Emission to air/unspecified	0.00019	kg		none				
Sulfur dioxide	Emission to air/unspecified	0.00019	kg		none				

Figure A.6: Input and Output flows in the rail transport that is considered for the sensitivity analysis

Figure A.7: Model graph showing the link between different processes in OpenLCA

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