CHALMERS
UNIVERSITY OF TECHNOLOGY

Sustainable impact assessment of Augmented Reality implementation at Volvo Group Truck Operation (GTO) Remanufacturing

Master's thesis in Production Engineering

LISHITH KUMAR GANGASANDRA SHIVAKUMAR
NIHAR MOHAN

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

MASTER'S THESIS 2020

Sustainable impact assessment of Augmented Reality implementation at Volvo Group Trucks Operation (GTO) Remanufacturing

LISHITH KUMAR GANGASANDRA SHIVAKUMAR
NIHAR MOHAN

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

Sustainable impact assessment of Augmented Reality implementation at Volvo Group Trucks Operation (GTO) Remanufacturing
LISHITH KUMAR GANGASANDRA SHIVAKUMAR, NIHAR MOHAN

© LISHITH KUMAR GANGASANDRA SHIVAKUMAR, NIHAR MOHAN, 2020.

Supervisor: Xiaoxia Chen, Department of Industrial and Materials Science
Examiner: Mélanie Despeisse, Department of Industrial and Materials Science

Master's Thesis 2020
Department of Industrial and Materials Science
Division of Production Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Remanufacturing of truck engine .

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2020

Sustainable impact assessment of Augmented Reality implementation at Volvo Group Trucks Operation (GTO) Remanufacturing

LISHITH KUMAR GANGASANDRA SHIVAKUMAR
NIHAR MOHAN
Department of Industrial and Materials Science
Chalmers University of Technology

Abstract

Today, the manufacturing industries are adhering to the industry 4.0 revolution and promoting to incorporate the digital technologies to their operations to enable efficient production systems. Simultaneously the industries are also progressing towards sustainability, in order to reduce the negative environmental impacts that mainly cause by the production. Reducing environmental impacts not only protects the climate but it also helps to attract more customers. It tends to motivate the customers to contribute to the environment by purchasing the products that processed in a most sustainable way. In a way, remanufacturing is considered to be one of the most sustainable methods of treating a product at its end of life. Manufacturing companies have begun to realize that products that are discarded at the end of their usage phase still have various components that can be reused instead of being recycled. The benefits of remanufacturing are that it utilizes fewer resources, less energy consumption, and reduces waste. The optimization of the remanufacturing process with the implementation of digital technologies is one of the methods to accomplish even more sustainable benefits from remanufacturing.

This study aims to identify an optimal method for assessing the sustainable performance of the Volvo GTO and evaluate what will be the environmental benefits of implementing AR. This study begins by identifying the processes involved in the remanufacturing plant. By adopting the Quantitative and Qualitative approach for the project, the method to evaluate the sustainable performance of the company, and the benefits of implementing AR are obtained.

By the end of the report, the readers can find the results accomplished from the study. The method and results aid the company to evaluate its sustainable performance and to identify the contribution of each process involved in the remanufacturing process to the environment. Also, the main contributor to causing the negative impacts on the environment is identified. By analyzing the several case studies of AR implementation in the remanufacturing industries, what will be the similar potential improvements that can be anticipated from the implementation of AR at Volvo are listed. The project team also suggested some significant tools for an environmental assessment for the company as recommendations.

Keywords: Remanufacturing, Augmented reality (AR), Sustainability, Environmental assessment

Acknowledgements

We would like to express our sincere gratitude to all the people who have supported directly and indirectly in making this project successful.

Firstly, we express our heartfelt gratitude to Chalmers University of Technology, Göteborg, and Volvo Group Truck Operation (GTO), Flen, for providing an opportunity to perform our master thesis.

We would like to express our special thanks to our examiner Mélanie Despeisse and supervisor Xiaoxia Chen for believing us to perform this project and for the support given at each phase of the project by providing constructive feedback and suggestions. To be mentioned, during the Covid-19 pandemic while facing difficulties to perform the project the guidance from our supervisor Xiaoxia Chen helps us to continue our work without obstructions.

Also from Volvo Group Truck Operation, we would like thank Abdulfatah Tarek for providing resources regarding the remanufacturing plant and for his continuous support towards the completion of our thesis. We would also like to say thanks to the research assistants of the university of Skövde for answering our questions about implementing AR.

Thanks to our families and friends for always stood behind us for support.

Contents

List of Figures

List of Tables

Acronyms

AP Acidification potential.
AR Augmented reality.

GTO Group Truck Operation.
GWP Global warming potential.

HTP Human toxicity potential.

LCA Life cycle assessment.

MEP Marine eutrophication.

PMFP Particulatee matter formation.

WCED World Commission on Environment Development.
WDP Water depletion.

1 Introduction

Remanufacturing plays a significant role in the end-of-life process to bring back the used products to the original equipment manufacturer's performance. It is distinctly contributing to the circular economy where the products are manufactured, used, and recovered to avoid the production wastes and reduce the extraction of raw material. According to studies from Gunasekara et.al prove that remanufacturing is more sustainable when compared to the original manufacturing [1], furthermore explained that remanufacturing owns the ability to achieve sustainable production that aims to produce products with generating less waste and pollution. Ijomah et.al explained that remanufacturing can reduce raw material consumption and energy usage compared to the original production [2]. Abbey et.al explains remanufacturing help in closing the material loop and reducing landfilling [3].

1.1 Background

Sustainable development plays an increasingly important role in manufacturing, covering triple bottom lines of economic, environmental, and social aspects. Digital technology promotes manufacturing efficiency with the progress of industry 4.0, which is mainly driven by reducing costs and increasing quality. Remanufacturing is one of the major contributors to sustainable development for the manufacturing sector. It benefits in extending the life cycle of the products contributing to the circular economy. The remanufacturing process mainly includes the phases disassembly, cleaning, inspection, restoring, and reassembly [4] [5]. Disassembly plays a crucial role in these remanufacturing processes and other end-of-life strategies like recycling and reusing [6]. However, disassembly is usually considered as a non-value-added activity as it requires extra effort and cost [7]. Hence, the disassembly process should be optimized to obtain a cost-efficient and environment-friendly operation [7].

Volvo Group Trucks is one of the largest medium to heavy-duty truck manufacturers in the world with a net sale of 390,834 trucks in the year 2018 [8]. Volvo group relies on the core values Quality, Safety, and Environment. Environmental care has been a core value since the '70s, in following that value they have reduced the emission of air pollutants by their trucks up to 90% and CO2 by 40% [9]. Volvo Group strives to minimize the environmental impact of its operations by concentrating on the effective use of energy and water, by using safe chemicals, reducing air emissions, by increasing recycling, reducing waste, and remanufacturing. They focus on every part of their process to identify any necessary changes to lower their impact. As for the latest update of the Volvo group plan for the future, they are mainly focusing on crucial areas of automation, Co2 reduction, efficient energy, and future vehicle architecture.

The engine remanufacturing process in Volvo Group Trucks Operations (GTO) plant is adopting Augmented reality (AR) technology to their disassembly process. It is of interest to assess the sustainability implication from the technology implementation, as an important indicator to evaluate the utilization of resources such as raw material, energy consumption and manpower to ensure a cost-effective and sustainable process.

Volvo believes that with the growing popularity of remanufacturing, it can be a key way to become a sustainable company by redesigning and innovation in remanufacturing. Prior to this, the Remanufacturing plant at Flen, Sweden is now planning to introduce an AR technology in the remanufacturing process anticipating a significant improvement in their sustainable performance.

1.2 Project aim

The aim of the project is to quantify the sustainable impact of AR implementation in the engine remanufacturing process at Volvo Group Truck Operation (GTO) .

1.3 Project objectives

Evaluating the environmental benefits of AR implementation at the remanufacturing process. Finding an optimal method for assessing the environmental performance of the current remanufacturing site at Volvo and suggesting the other sustainable assessment methods to assess sustainable performance after implementing AR.

1.4 Project limitations

The sustainability concept includes three categories such as environmental, economic, and social values. The sustainability assessment in this study refers only to the environmental assessment. Due to the time limits and to align the study with the project goal, the economic and social assessment are excluded. Therefore, the term sustainable here mainly refers to the environmental factor.

1.5 Research questions

In order to comprehend the sustainable performance of the Volvo remanufacturing plant and analyze the changes with implementing AR, the following two questions are raised

1. How to assess the sustainable performance of the current remanufacturing process of Volvo?

2. How will the implementation of AR at the disassembly process impact the environmental performance in the future?

2
Theory

.

2.1 Remanufacturing Process

Remanufacturing is one of the industrial processes that allows bringing back the used or damaged products to the new condition [10]. with the industrial revolutions and exponential growth in the world population, the industries all over the world dealing with the huge increment in material/non-renewable energy consumption. In order to control this scenario that threatens the future, the World Commission on Environment Development (WCED) introduced the concept called sustainable development to provide solutions to the high consumption of environmental resources [1]. Adopting sustainable development in the manufacturing sectors, the strategy of producing goods changed to sustainable production reducing the utilization of resources with less emission and waste [1]. Remanufacturing is one of the major contributors to meet the sustainable manufacturing goals, as it promotes closing the material flow loop, prolongs the product life cycle, and reduces material consumption [10]. Remanufactured products consume minimum energy and less material usage when compared to the original products, thus proving remanufacturing is a more sustainable process [1]. Remanufacturing is increasing its value in the industries like construction equipment, machine tools, medical and aviation equipment, and automotive components. Nowadays, remanufacturing of automotive components is on the rise due to its large market demand [11], engines are the most commonly remanufactured automotive component today [12]. The statistics on remanufactured engines showed that among the engine parts, 23.7% in quantity, 14.4% in weight, and 12.3% value could directly be reused and after remanufacturing it is increased by 62% in quantity, 80.1% in weight, and 77.8% in value [12].

2.1.1 Steps involved in the remanufacturing process

The remanufacturing process typically includes processes such as disassembly, cleaning, inspection, repairing, or replacing the defective parts, reassembly, and testing [12]. Used or worn products go through all the processes to regain its original quality. The transformation of the input into output through the re-manufacturing process scarcely presented below using IDEFO diagram level A0 [10].

The IDEFO diagram level 0 in Figure 2.1 shows Input (I), Output (O), Control C, Mechanism (M). The input to the process includes old products arriving for the re-

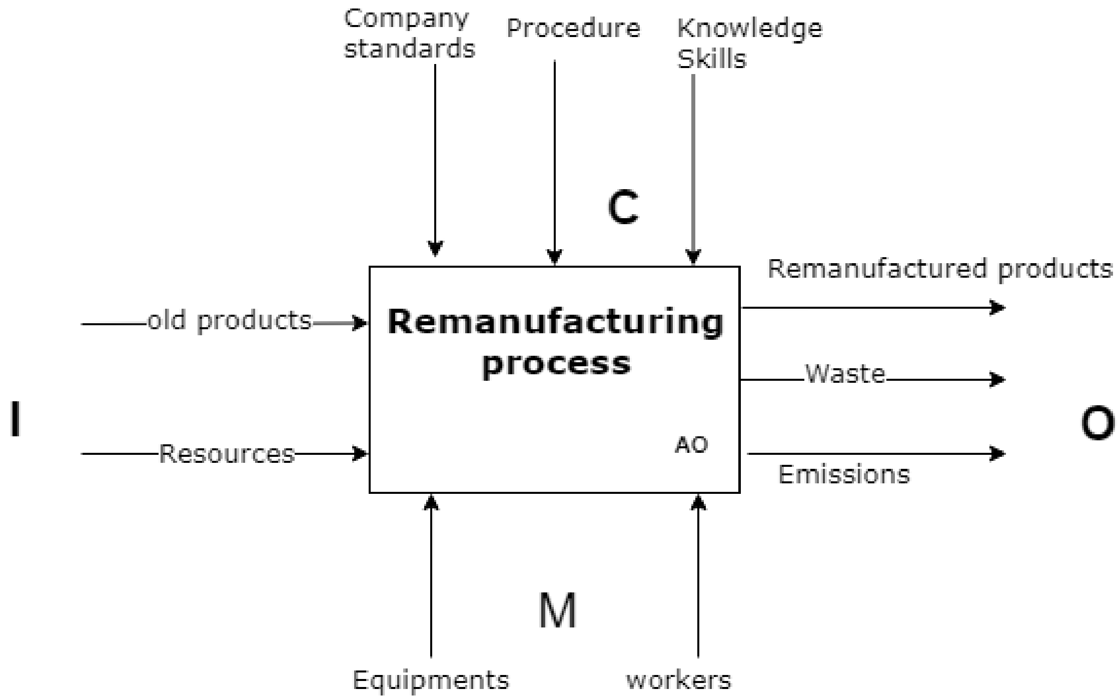


Figure 2.1: IDEFO diagram Remanufacturing process

manufacturing and the required resources to perform the necessary operations. The resource mainly includes electricity, water, ancillary materials. The process includes required operations of the remanufacturing process with the support of the skilled employees, equipment, company standards, and procedures. After completing the remanufacturing process, it results in the outputs includes remanufactured products, waste from the process, and the corresponding emissions from each process.

The first phase of the remanufacturing process is disassembly where the product components are removed from the core. The disassembly process should be carried out with precision and care in order to avoid damage to the parts. The parts having the remanufacturing ability will be cleaned and inspected to carry out the further process. After passing the inspection test the parts go through the repairing stage and get fabricated to its original condition if necessary. The operation involved in this stage usually depends on the type of components and the operations that are following in the respective industries [10]. The fabricated parts along with missing parts needed for a product are arranged before reaching the reassembly station, and the assembly process will be carried out to the remanufactured product. After the assembly process, the products are tested and validated to meet the required standards and packed for dispatch.

2.2 Sustainablity

The world commission on environment and development in 1987 stated that 'sustainability is an activity that meets the needs of the present without compromising the capability of future generations to meet their own needs' [13]. The basic concept of sustainability is to not deplete and damage the earth's resources indefinitely. Also, it is more about maintaining the steady-state of the earth's resources to support human needs without threatening the health of the humans, plants, and animals [13]. The sustainability concept consists of mainly three elements such as environment, economic, and social values. These three elements are also called as three pillars of sustainability. Sustainability can be accomplished, when upholding all three elements such as conserving the environment, maintaining economic growth, and social values.

As the manufacturing companies face several challenges like resource depletion, customer demand on higher quality, and stricter laws and regulations, the manufacturing companies are focusing on the sustainable manufacturing method to deal with these challenges [14]. Sustainable manufacturing is defined as producing goods with processes that reduce the negative environmental impacts, conserve energy and natural resources, economic benefits, and are safe for employees [14]. In recent years, the remanufacturing strategy plays a significant role in maintaining sustainability in the manufacturing sectors. The remanufacturing is considered to be more sustainable because it involves the economic benefits of material and energy savings, environmental benefits of less emission and waste reduction, and social benefits of creating jobs and ensuring the safety of people [15].

Moreover, in order to engage the concept of sustainability, it should be measured [15]. In spite of the growing interest in remanufacturing, the assessment of remanufacturing in the context of sustainability is still an unexplored research topic [15]. However, one of the reasons for the lack of sustainable assessment of remanufacturing would be the complexity that includes it. Remanufacturing is often considered as a more complex process than manufacturing, due to the uncertainty involved in the steps and process time, and unpredictability of cores [16]. Consequently, this study focuses on the sustainable assessment particularly the environmental factors of the remanufacturing process.

2.2.1 Sustainability challenges of remanufacturing

Golinska et.al identified some main reasons causing environmental pollution from the remanufacturing companies and described it in the fishbone diagram (Ishikawa) shown in Figure 2.2 [10]. In manufacturing industries, the fishbone diagram is generally used for the problem analysis in the system and its root cause. Problems that are causing environmental pollution are categorized into four types that include employee, machines, materials, and remanufacturing process. Lack of ecological awareness in employees and lack of standardized work procedure is the reasons for causing pollution by employees. Lack of maintenance and following old technologies are the reasons for machines. Handling a huge waste and improper material sorting are the reasons for pollution by materials. Utilizing high energy in the process and more energy losses are the reasons in the remanufacturing process. These are the main types of problems mentioned in the fishbone diagram by categorization.

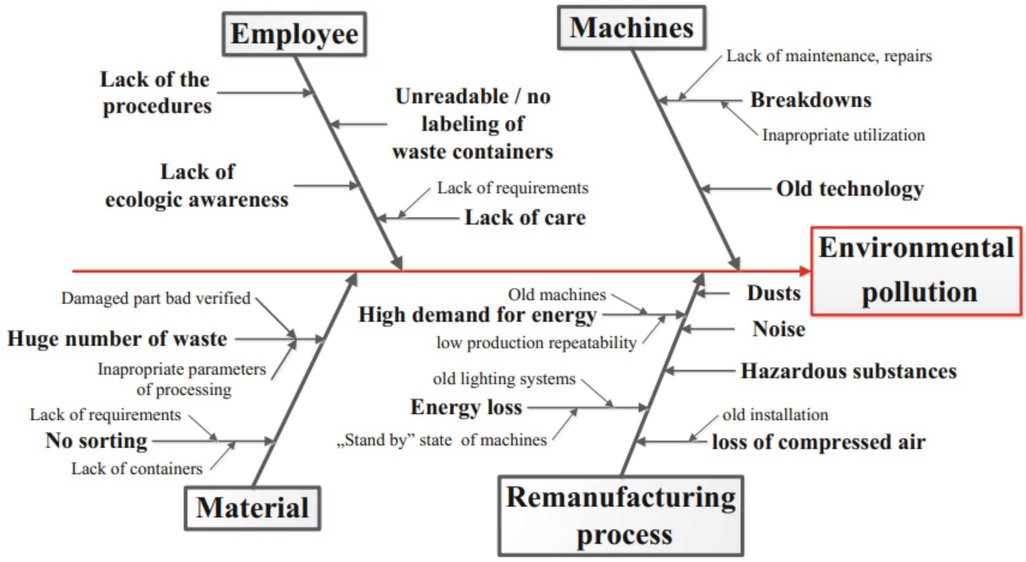


Figure 2.2: Ishikawa diagram for problems causing pollution in a remanufacturing company [10]

2.3 Disassembly process

Products after reaching the end-of-life stage can be returned to the life cycles in ways like recycling, reusing, and remanufacturing. At each end of life strategies including maintenance of the products require disassembly as the first stage [6]. However, the disassembly process is considered as a non-value adding activity as it requires additional effort and costs [7]. Thus disassembly needs to be improved to become a more efficient operation [7].

Disassembly is a systematic process for separating components, parts, subassemblies, and other groupings from a product [5]. Disassembly can be performed as partial, complete, destructive, and non-destructive ways [5] [6]. Partial disassembly is more adaptable for the remanufacturing process, certain parts that are capable of repairing/servicing are selected and taken out from a product. Most of the time complete disassembly is required for recycling when the products reach its end-of-life. Even though disassembly can be performed in a way that finds reasonable to the companies Tegeltija, et al. mentioned the list of activities that mainly included in the disassembly [17]. The activities included are:

- Receiving a product to the workstation

- Identifying the product type and variants
- Looking for a disassembly description for that product
- Performing disassembly
- Determining the condition of the disassemble products
- Component selection according to its condition and conveying to next process

As the product complexity and variants increase the time required for each activity to accomplish will increase, operator spending on identifying variant and product type is often considered as a loss for the system [17]. This situation results in a decrease in utilizing labor efficiency, machine utilization, and productivity. All these problems relate to reducing the efficiency of the disassembly process [17]. Since the disassembly sequences are differed by the product types, more cognitive aid is needed for an operator to perform disassembly by supplementing with the required information. In order to increase the overall efficiency of the disassembly process, several technologies have been implementing and testing its results, such as computer-aided drawing (CAD) based disassembly, Monte Carlo method, barcode, RFID and others [17] [6]. Augmented Reality (AR) is a newly emerging concept in the manufacturing industries that mainly supports the disassembly and assembly process by transforming relevant information in real-time [17].

2.4 Augmented Reality

Augmented reality is a human-computer interaction technology that provides virtual information on the real-world [6]. AR application technology was first introduced and applied by T. Caudell in 1922. It was developed to improve the efficiency of human workers performing manufacturing activities [18]. AR systems must have the ability to fulfill the following criteria such as a) ability to combine virtual and real content in a real condition b) real-time and interactive c) ability to register virtual content in a 3D environment [6].

Virtual reality VR technology was given the most importance in the early '90s at various manufacturing domains in designing the prototypes of the products, simulation, and virtual machining [7]. Since AR combines the real-world elements with the aid of the camera, and multimedia elements such as images, videos, 3D models, and animations, AR becomes more favorable compared to VR in manufacturing industries in facilitating real-life manufacturing tasks [6].

AR helps the user to see the real elements in virtual computer-generated objects [17].AR has been widely developing in the assembly and disassembly of the products by the strategies called AR-guided product disassembly (ARDIS) and product disassembly sequence planning [7]. The main objective of these strategies is to guide the user to assemble/disassemble the products by providing detailed work instructions,as shown in the Figure2.3. Farkhatdinov et,al developed an AR-based educational training that guides the user to disassemble the mechanical parts of a transmission step by step through an animation of a 3D virtual model using AR, by the medium of videos and 2D or 3D animations interactive instructions can be im-

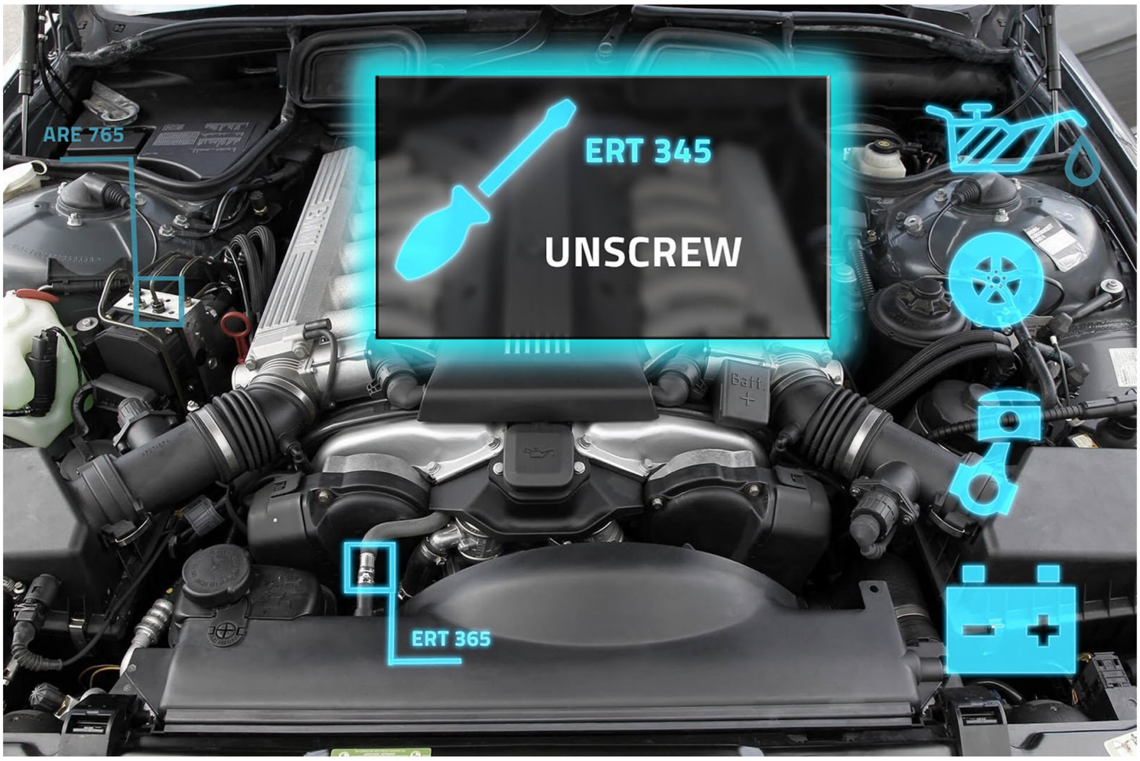


Figure 2.3: Augmented Reality (AR) applications in industries
[28]

plemented [18] . It concurs several advantages such as eliminating the time needed to train the new worker, reduces assembly time, the possibility of withdrawal of products when a minimal mistake occurs in assembly.

2.5 Life Cycle Assessment (LCA)

Life Cycle Assessment is an analytical method utilized to assess the environmental impact of a product or a system throughout its lifecycle. According to the International standard ISO 14040, LCA is defined as *"Assessing the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use, and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences."* [19].

Unlike the traditional Environmental assessment which mainly focuses on the environmental impacts during the production processes, LCA allows us to analyze and assess the environmental aspects and impacts involved throughout the product/system life cycle, following a concept of " From cradle to the grave". As a result, this analysis enables us to identify and reduce the waste and environmental impact involved, making the processes more sustainable [20].

The manufacturing industry uses LCA as a tool to reduce their product environment impacts by examining the inputs and output of the products. LCA practitioners survey of 2006 found that LCA is used for supporting business strategy, to improve process design, in research and development, labeling, and product declarations [21].

The main application of LCA are [22]:

- Comparing the improvement variants of the particular product
- Analyze the reason for a problem related to the product
- To design new products
- Choosing between the number of products

2.5.1 Steps in LCA

ISO 14040 describes the procedure to perform an LCA in four stages mainly; goal and scope definition, inventory analysis, impact assessment, and interpretation. Figure 2.4 represents the phases of LCA and the arrows explain each phase is an iterative approach.

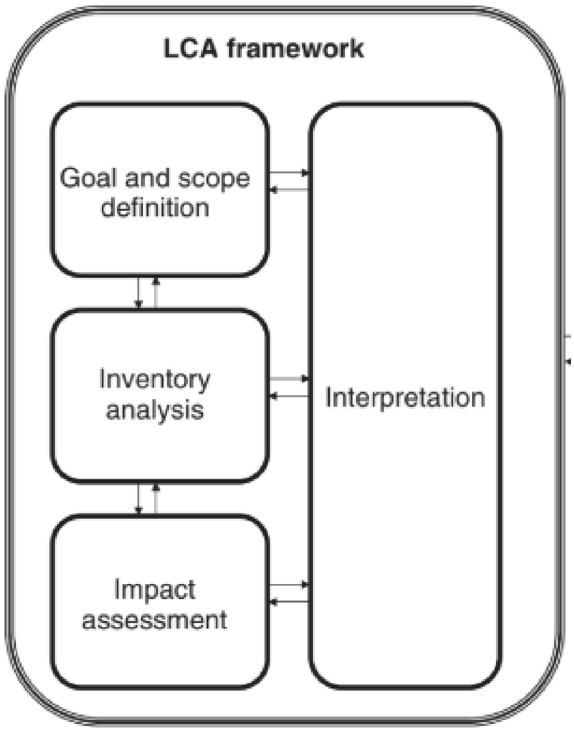


Figure 2.4: LCA phases according to ISO 14040

1. **Goal and scope**
   Goal and scope is the first phase of the life cycle assessment. In this phase, the purpose of the study and the decisions made about the details of the product system being studied should be described. The parameters should consider

while describing the goal are: functional unit as a quantified expression of the products, system boundaries, allocation procedures, selection of impact categories, data required for the process, and assumptions and limitations.

Functional unit: The functional unit provides a reference in which the inputs and outputs of the system are related [9]. Then the selection of the input and output to model the system depends on the functional unit.

System boundaries: system boundaries define the stage of the product life cycle to be included in the study with geographic and time boundaries, flows and impact categories included. Input and output flow outside the system boundaries are excluded. The process considered in a study is shared or connected between different product systems, allocation procedures are used to divide the environmental impacts over the different production systems.

2. **Inventory analysis**
   In this phase, data and information regarding all the inputs of a process such as raw material acquisition, energy consumption, and output such as by-products, emissions, and waste material obtained are all collected. Raw material, water, and energy consumption at each step of the processes are analyzed along with the outputs of the products such as finished product, emissions to water and air, and also the recyclability of materials.

3. **Impact assessment**
   In this phase, the environmental impact of these outputs is analyzed on the basis of Inventory analysis. To find potential improvements to make the processes more environmentally friendly the inventory results are categorized into their respective environmental impact categories such as global warming, acidification, eutrophication, ozone depletion, etc. life cycle impact assessment consists of three mandatory steps (classification, selection, and characterization) and two optional (normalization and weighting) steps.

   The classification includes classifying the inventory results according to the selected impact categories. The selection includes selecting the impact categories, category indicators, and characterization model related to the study. Characterization includes converting inventory results into the category score for each impact category. Normalization includes magnitude calculation of the indicator results relative to reference information and weighting includes aggregating the single score of the impact assessment.

4. **Interpretation**
   In this phase, based on the analysis of Inventory and impact assessment the potential areas of improvement are identified. Further testing and verification of these suggested improvements will be implemented into the production process making it more sustainable. 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.

2.5.1.1 Life cycle impact assessment methods

By applying various types of Life Cycle Impact Assessment (LCIA) methods generates a significant difference in the corresponding quantification result, which makes interpretation difficult. In order to obtain a correct interpretation, proper documentation and transparency of the applied Life cycle inventory (LCI) and LCIA data are essential [23]. There are several LCIA methods available to evaluate the environmental impacts such as (ECO-Indicator 99, EDIP, USES-LCA, IPCC 2007, CML 2001, BETR, ReCiPe, and several....) [23].

According to ISO 14040, life cycle impact assessment (LCIA) is a phase of LCA, evaluating the magnitude and importance of the environmental impacts of the product system [19]. This is one of the supportive steps in the LCA study. 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 desired result.

Weighting method is one of the LCIA methods used in the LCA study, it is a process of converting different impact categories results by applying numerical factors based on value choices [19]. The weighting method assigns the clear quantitative weights to each impact category expressing their relative importance [22]. Different weighting methods such as EDIP for calculating Human Toxicity and acidification potential, and ReCiPe for identifying Marine Eutrophication, Particulate matter formation, and Water depletion. One of the non-weighting methods IPCC 2007 for identifying Global Warming Potential is used in this study.

ReCiPe derives the environmental scores in two ways either midpoint or endpoint level. Midpoint indicator level concentrates on the single environmental issues, the endpoint indicator level concentrates on the environmental impacts on three higher aggregation levels: human health, biodiversity, and resource scarcity.

OpenLCA software calculates the results by utilizing the data from the life cycle inventory. By applying the suitable impact assessment method for the collected data it is possible to obtain the results for environmental impact categories that are listed in Chapter 2.5.1.2. Life cycle inventory data are the input and output data of the remanufacturing process explained below. The life cycle impact assessment method will transfer the inventory data into scores of respective environmental categories.

2.5.1.2 Life cycle impact categories

To be consistent 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 Particulatee matter formation (PMFP).

1. **Energy and material use**
   The amount of energy and material consumption during the remanufacturing phase, energy generally represents electricity and water.

2. **Global Warming Potential (GWP)**
   The global warming potential measured over a 100-year time horizon by calculating kg CO2 equivalents. The substances contributing to the GWP are carbon dioxide, methane, and nitrous oxide. 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. GWP is commonly used for assessing the environmental impacts of a product.

3. **Acidification potential (AP)**
   Acidification potential measured in kg SO2 equivalents. Substances contributing to the acidification potential are ammonium, nitrogen oxide, etc results in lowering the pH values in soils, water, and ecosystem.

4. **Human Toxicity Potential (HTP)**
   Heavy metal components such as mercury, lead, etc are released during the production process causing the adverse effect of human health. It can be released through the air, water, and soil to the atmosphere.

5. **Marine Eutrophication (MEP)**
   Eutrophication is enriching the nutrients in the body of water by human activities which causes excessive algae growth in water bodies which leads to reduced oxygen content in the water. Substances such as sulphur dioxide and nitrous oxides acidify the water and soil [24].

6. **Water depletion (WDP)**
   It's a way of measuring water consumption in the production process. Measuring the footprint of water to ensure no scarcity for freshwater in the future.

7. **Particulate matter formation (PMFP)**
   Particulate matter (PM) is a mixture of small particles of organic and inorganic substances. A primary particle is directly emitted from the sources and secondary particles chemically react with the atmosphere causing severe health problems [24].

2.5.1.3 Benifits of LCA

- LCA helps to choose between alternative measures by giving information about the environmental impacts of the different alternatives

- LCA results can help the management in the decision-making process by providing environmental impacts when selecting a product or process
- LCA includes the consumption of resources like energy or carbon emission regardless of where the process is located
- Through LCA the most efficient way of increasing environmental performance of the product can be identified
- Results of LCA can be used to convey the environmental benefits of the products to the customer

3
Methods

3.1 Data collection

3.1.1 Literature studies

The initial aim of the literature study is to gather information about the current remanufacturing processes and how it is contributing to the environment. In order to reach the current project aim, more studies have been performed to find out the relevant information about the Disassembly process, Augmented Reality, and Sustainable assessment. The keywords used while searching the articles are listed:

- Remanufacturing
- Disassembly
- Sustainable manufacturing
- Augmented Reality
- Sustainability measurement

By applying the method of filtering explained by Schirone and Volkova [25] it is manageable to narrow down the search results. Because, while searching the articles with simple key words the results obtained are extensive. Initially, found 12,000 research articles related to the keywords entered, which were published after the year 2005. Utilizing Boolean logics, removing the duplicate results, exact phrases such as 'sustainability in remanufacturing' 'sustainability assessment' 'augmented reality benefits', and saving search strings [25] made it possible to get relevant articles. The results were narrowed down to 380 papers after filtering. In that, 150 papers were selected after reading the abstract and following the content and structure of the papers. After reading the selected papers, further 90 papers were excluded from the reason for diverging aim and findings. Consequently, 60 papers were selected for the study, and 33 papers were included for the analysis of high relevance to the project goal. The main search engine adapted in this study is the website of Chalmers Library and Scopus. From the Chalmers Library, it is made possible to be redirected to the other databases such as Sciencedirect, Web of Science, and Researchgate.

In order to achieve a goal of finding an answer to the research question 1. How to assess the sustainable performance of the current remanufacturing process of Volvo. A list of sustainable assessment tools that have been used all over the world is reviewed from the literature surveys. According to Andersson et al. the methods and tools for the environmental assessments can be grouped into three categories [26]:

1. Procedure tool
   Procedure tools used for defining the procedure of assessments without considering a relative description of the qualitative and quantitative steps in the assessment [26]. This tool considers all three sustainable aspects including environment, economic, and social. Some examples of procedural tools are Environmental impact assessment, Scenario analysis, strategic impact assessment, and Risk management which certainly used to find decisive support for development projects.

2. Analytical tools
   Analytical tools mainly used to quantify energy, material, and economic flows in a system often followed by valuation and aggregation [26]. There are several analytical tools, in which the LCA tool is the widely used, internationally accepted standardized tool by ISO 14040 and 14044. LCA is considered as a valuable methodology for environmental monitoring and precautionary environmental protection. Also, this method acts as a decision making process regarding sustainability [27]. The application of LCA helps industries in the design of the products and production process, environmental strategy, and waste management to achieve sustainable production [27].

3. Aggregated tools
   Aggregated tools are used to analyze the measured or collected data and after that, it can be communicated in the form of indicators and into indices [27]. To control and communicate a complex system, the aggregation of the information into a way that easily and distinctly communication is necessary.

To assess the sustainable performance mainly environmental at remanufacturing plant Volvo, one of the analytical tools LCA is selected as it mainly focuses on quantifying energy and material flows in a system. Life cycle assessment is an environmental impact assessment of the product's life cycle from a cradle to grave perspective that is the extraction of raw materials to waste management [26]. Every activity in the product life cycle considering resource usage, waste, and emission is described quantitatively [20]. The resource usage, waste, and emission at each activity are summarized into the environmental profile of the products called life cycle inventory (LCI) and it can be classified into different groups depending on which environmental aspect it affects.

3.1.2 Plant visit and Interview

In order to assess the sustainable impact of implementing AR at remanufacturing plant Volvo, firstly it is essential to assess the current remanufacturing process. To be able to perceive how the remanufacturing process is being performed currently, the following questions are investigated.

1. What are the steps and processes involved to complete the remanufacturing

of a product?
2. The number of workstations and how the operators are performing their operation in each station?
3. What will be the quality and performance of the remanufactured products over original manufactured products?

Interviews are decided as the main approach to finding answers to these questions, the first formal interview was carried out during the factory visit. This visit is carried out at the initial stage of the project. The factory is located at Flen, Sweden which is 400km away from the Chalmers. Before visiting the factory, the questions are formulated for the interview as a pre-interview stage. After the factory tour, the interview was performed with the production manager and collected the information that could not be found during the factory tour. During the interview, more about the remanufacturing process, what are the types of trucks involved in remanufacturing, detailed information about how the disassembly process is performing, and what are the energy required to perform those operations are noted down. The data that is collected in this step is analyzed and the information which is not related to the project focus is excluded.

After performing the literature surveys and identifying the method for the sustainable assessment, the data required for that assessment method are planned to be collected through interviews. Further factory visits are not carried out due to the unpredictable new limitations formed during the time period of the project. To find out the information related to LCA, the following questions are framed.

1. What are the inputs and outputs at each workstation of the remanufacturing process?
2. What are the values for the electricity and water consumption at each process and also the wastes at each process?
3. What are the components in a truck engine?

Five Skype interviews were conducted with the industry supervisor. Tarek Abdulfatah is a manufacturing technology specialist at Volvo GTO, who is responsible for the supervision of this project. Before each interview, a questionnaire was sent by e-mail to the interviewee for preparation. Semi-structured interviews were also employed to find out more information related to the project and having a discussion on the findings accomplished. Only partial data such as a component list of the truck engines and inputs and outputs at each process are collected through these interviews. The remaining data regarding the energy consumption of the process are difficult to obtain due to the temporary shutdown of the factory. These data are obtained through the literature studies and validated by industry supervisor.

The information regarding the AR. How the implementation of AR will be performed, how the AR guides the operators to perform the operations, are collected from Victor Igelmo, a research assistant University of Skövde, Sweden. The University of Skövde is part of the Rewind project together with Chalmers University and Volvo remanufacturing plant, responsible for the implementation of Augmented reality. Two semi-structured Skype interviews were conducted with Victor Igelmo and the information related to the AR implementation was found out.

3.1.3 LCA

The following benefits are considered when choosing LCA for the project [20]

- LCA is standardized by ISO 14040 and 14044 providing detailed technical guidance
- Possible to assess the numerous environmental impact categories such as abiotic depletion (ADP), acidification potential (AP), global warming potential (GWP), primary energy depletion (PED)
- LCA can help the management in making a decision regarding the production process and services
- System boundaries can be freely set according to the project goal, the systematic outlook is possible depending on customer requirements

There are several tools available to perform LCA providing a variety of databases. Open LCA is an open-source software tool developed by GreenDelta. Open LCA is chosen for this study because it is a user-friendly, freely accessible tool providing fast and reliable calculations and suitable for using sensitive data. It offers the largest collection of databases and choice for the impact methods, users can select the database and impact method depending upon the type of the study.

3.1.3.1 Goal and Scope

LCA generally covers all phases of the product that includes: raw material extraction, transportation, manufacturing, use, and waste management. There are several databases available to provide the necessary information about the consumption of raw materials, energy, and land resources and the emission corresponds to each phase of the product. On the contrary, there is a lack of databases to analyze the environmental impacts of the products in the remanufacturing phase, as there are only a few LCA studies available that are based only on remanufacturing.
LCA has been considered for this study because it is an essential and powerful decision support tool that helps to avoid generating waste-related issues while improving production technologies and accompanies the method that efficiently makes consumption and more sustainable production [22].

The aim of this LCA study is to assess the potential environmental impacts of the engine remanufacturing process of the Volvo group trucks operation. Assessing material usage, energy consumption, and emissions that cause negative impacts on the environment at each workstation, and analysis of the results. Also, compare the results with AR implementation whether it can contribute to reducing environmental impacts or not.

3.1.3.2 Product definition and functional unit

The Remanufacturing plant at Flen is a truck engine remanufacturing plant where it collects the used or worn truck engines from the customers and replaces them with an exchange part. This exchange part can be new or remanufactured. Volvo classified its trucks into four categories: regional distribution, city distribution, long haul, and constructional trucks. Remanufacturing is performed to all series of trucks. Since this study aims to evaluate the environmental impacts of the remanufacturing process, the functional unit (FU) of this study is considered as measuring the environmental impacts of an engine when it is processed through the current remanufacturing process.

3.1.3.3 System boundary

This study is to explore the environmental impacts of the Volvo remanufacturing process and analyze the AR contribution to their sustainable performance. This study only concentrates on the process included in the remanufacturing plant. The raw material acquisition, necessary transportation to the plant, products leaving the plant, and its use phase are all excluded. Figure 3.1 shows the representations of the system boundary.

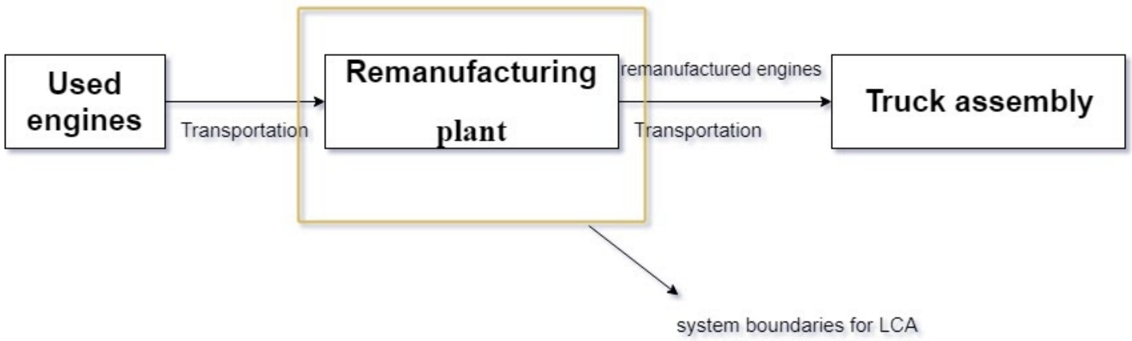


Figure 3.1: System boundaries for LCA study

3.1.3.4 Limitations

The AR implementation is an ongoing process and its implementation time does not match with the current project time period, environmental assessment after implementing AR cannot be performed.While performing an LCA study, waste management usually refers to the waste after the usage phase of the product. Since the usage phase is not considered in this study, waste management referred to in this study is the waste obtained by the manufacturing process. This study concentrates only on the remanufacturing process at the same time in house transportation between the workstations and inventory is not considered for the calculations.

3.1.3.5 Assumptions

The Flen remanufacturing plant performs remanufacturing operations on all the different types and variants of truck engines manufactured by Volvo. For this study, remanufacturing of only one type of truck engine is considered. The input values at the different stages involved in the remanufacturing process are obtained from literature studies due to lack of access to from the plant due to the pandemic.

3.1.3.6 LCA Database

Ecoinvent has more than 20 years of experience in the development of LCA methodology and compilation of LCI data for different industrial sectors. With around 17000 LCI datasets in various areas including energy supply, transport, materials productions, wood, and waste treatment. Ecoinvent version 3.6 database is used in this study with more than 2000 new updated datasets that provide the most relevant, transparent, consistent, and reliable datasets. Since it is not possible to collect the data precisely related to the remanufactured engine components, data about the materials that used in the components of engine are considered for the study.

3.2 AR implementation

The implementation of the Augmented reality system at the Volvo remanufacturing plant at Flen is guided by a research group from Skövde University who are part of the Rewind project together with Chalmers University and Volvo remanufacturing plant. The AR tool will be implemented at the Disassembly station in the remanufacturing process in order to assist the operator at this station to perform the task efficiently and effectively. The AR tool is being implemented at the disassembly station initially due to the fact that the Volvo remanufacturing plant is remanufacturing truck engines built from 1975, this results in a lot of variants of engines and in turn a large number of instruction manuals that the operator needs to access to complete his task correctly. In order to choose the right AR tools to assist the operators, interviews with the operators were performed which furthermore resulted in choosing a handheld or mountable AR tool compared to the head-mounted AR tool such as the Oculus. From the interviews with Victor Igelmo, it was established that the operator preferred the Handheld AR tool as opposed to the head-mounted AR tool as they felt that the latter would obstruct their vision while performing the tasks. The handheld AR tool would be easier to access and use as shown in Figure. It can be used to scan the Truck engine for access to the data and obtaining the instruction manuals, the operator can then carry out his task without any obstruction.

This AR tool is connected to the Product Database Management system that contains data regarding all engine models, and when a truck engine is scanned it will provide the operator with the specific component list and instruction manual for that specific engine. With this information, the operator can perform his tasks

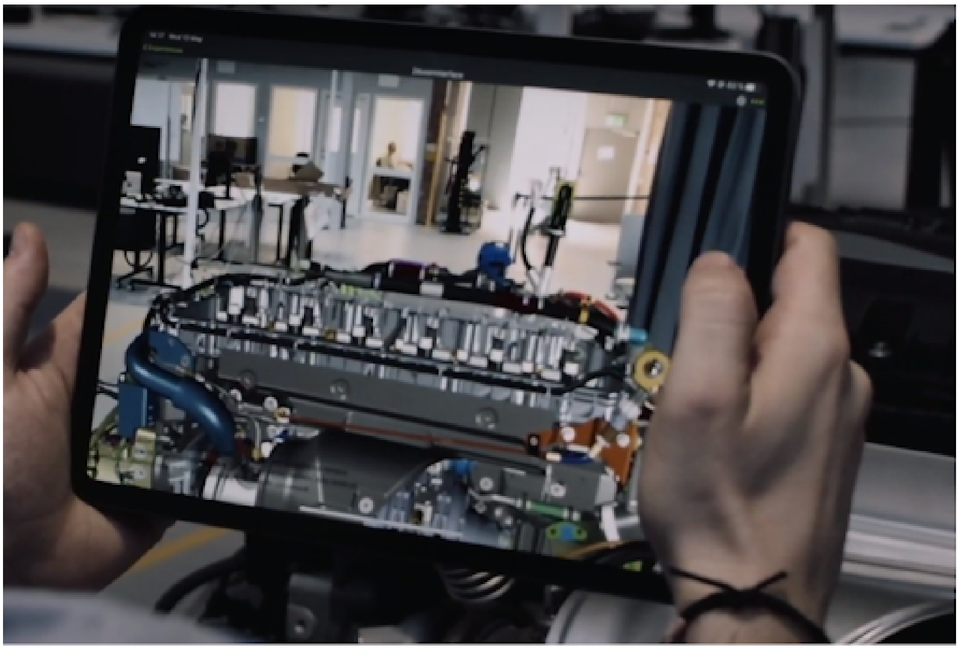


Figure 3.2: AR tool

much efficiently and without error thus completing the task in reduced time and using lesser resources such electricity furthermore ensuring better quality of products by ensuring zero error in the performed task.

4
Results

The results achieved during the project work are provided in this chapter.

4.1 Data collection

4.1.1 Remanufacturing process

Figure 4.1 depicts the general sequence of the steps involved in the Volvo remanufacturing process, the remanufacturing process is carried out by processing the eight different steps. Initially the process map is developed in order to understand the complete processess that involved in the remanufacturing system. figure 4.1 is obtained based on the information collected from the factory visit and experts interviews at Volvo.

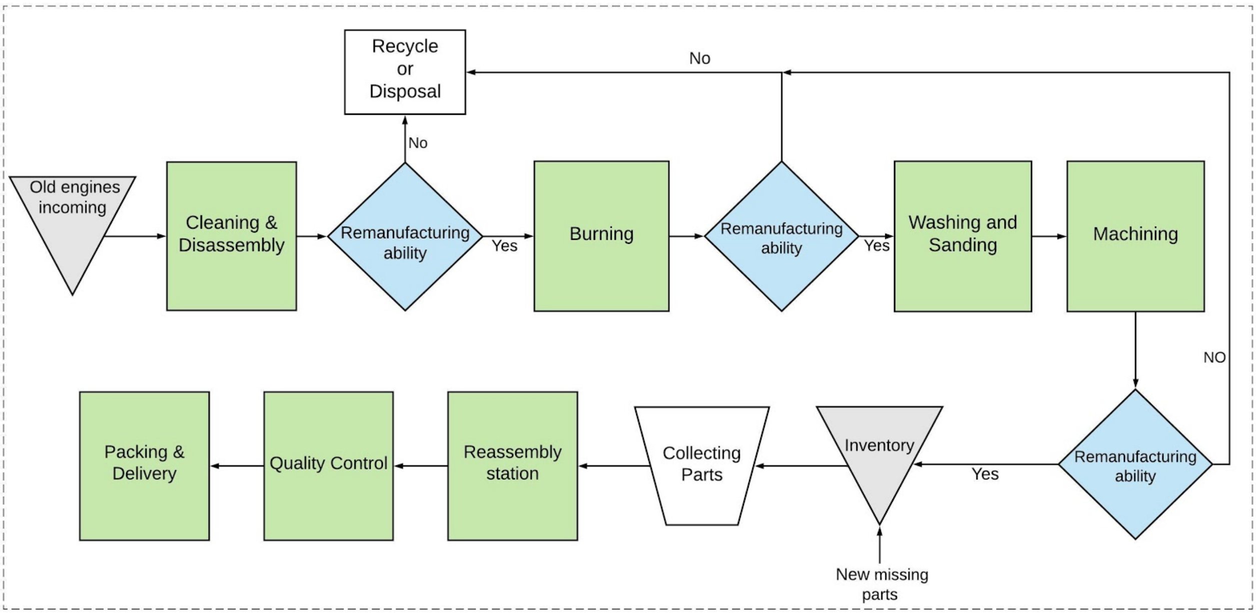


Figure 4.1: Volvo remanufacturing process

- **Step 1: Disassembly and cleaning**
  Old engines received from the different regions are subject to primary cleaning to remove dust and grease accumulated on the engine surface to perform the disassembly process. The remanufacturing process begins with dismantling the parts, the entire engine is taken apart and all the electronic parts are sent

to the scrap. Disassembly usually carries out by using the power drill tools. The dismantled parts that possess the remanufacturing ability will be sent to the next workstations and the parts which are seriously damaged that are not worth remanufacturing are sent for the recycling of the components. Condition analysis of the components and the procedure for dismantling the products is completely dependent on the worker skill. Disassembly time generally depends on the product complexities, at the plant in Flen, over 150-200 types of truck engines are remanufactured and for that, the disassembly time would vary for each variant of engines. Engines from the 1970s and the engines that are in a critical condition would take more time compared to the normal ones. Since it requires more time and good knowledge for condition analysis of the components, it is considered as one of the important steps in this remanufacturing process.

- **Step 2: Burning**
  The components that are difficult to disassemble due to the clog formation of the grease and hard joints are subject to burning. The components are heated to the required condition and help for further complete disassembly. The remanufacturing ability of the disassembled components are further analyzed and proceeded to the next processes.

- **Step 3: Washing and sanding**
  The parts that possess the remanufacturing ability are sent for cleaning. The oil residue, burnt trace, moisture, and the old paint that resides on the components are removed in this process and sent to the machining process.

- **Step 4: Machining**
  The remanufacturing components are sanded and milled with great precision and care to meet the standard of new parts in terms of surface roughness, dimensional accuracy. The processing time depends on the quality condition of the products. The components that reflect good quality condition would just require cleaning and surface finishing. However, components that are in the worst condition definitely require machining along with the cleaning and surface finishing.

- **Step 5: Collecting parts**
  The parts after machining which meet the standards of the new parts are sent to the inventory. The other parts that do not involve in remanufacturing are imported from the original equipment manufacturer. The inventory contains all the required parts both remanufactured components and original components, to reassemble the engine. The parts required for the reassembly of an engine are collected with the help of a kit wagon and transferred to the reassembly station.

- **Step 6: Reassemble**
  The individual components that have been separated from the engine are re-

assembled here with the new parts. The kit wagon includes all the required parts for an engine and the operator will collect the parts and reassemble the engine. The assembled engine includes both the remanufactured and original manufactured parts. The engine reassembled here should pass all the tests as a newly manufactured engine.

- **Step 7: Quality control**
  After reassembly, the parts are tested according to the standards of the new parts. The engine is thoroughly examined and assures everything is optimized from fuel access to the software.

- **Step 8 : Packing and delivery**
  In this station, the engines are packed well so that it should not lead to any damages during transportation. Engines are packed with the cardboard, wood, plastic covers so that it should support the engine and ensure it can ship to long distances as well.

4.1.2 Life cycle inventory

Life cycle inventory is a collection and quantification of the inputs and outputs of a product through its lifecycle [1]. In this chapter, the inputs and outputs related to the engine remanufacturing process are presented.

4.1.2.1 Inputs and outputs for the LCA model

Production inputs and outputs considered for the LCA study is presented in this section.

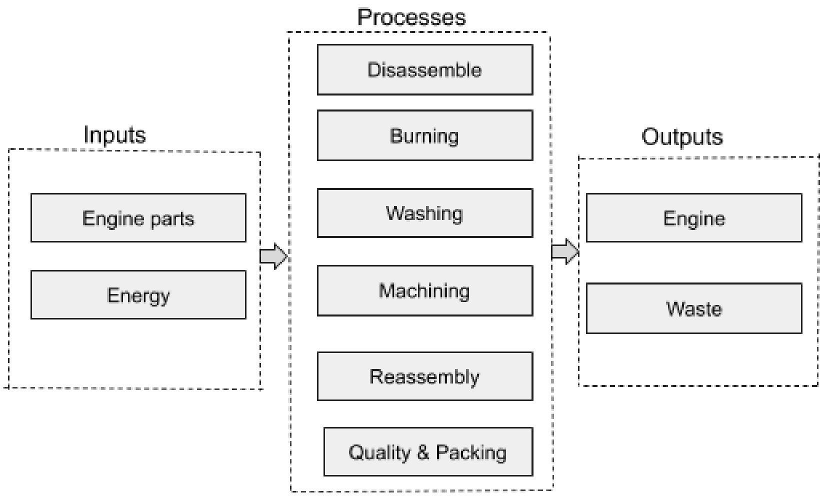


Figure 4.2: Input and outputs for LCA model

The engine parts and the energy consumed at each process are the two inputs for each workstations. Engine parts represent the components of an engine. For this

LCA study, depending upon the weight and cost of the components, some of them are considered as the most important components in an engine. The Identified important components, material, and weight are presented in Table 4.1. The main components are selected after analysing the Bill Of Materials (BOM) of an engine which received from the Volvo,and its materials and weight are collected from a literature paper Zheng et.al [12]. The data regarding energy consumption such as electricity, water, and other resources at each workstation are supposed to be gathered from the factory visits and through interviews, but due to the temporary shutdown of the factory because of the pandemic, those data are gathered from a research study of engine remanufacturing by Zheng et.al [12]. The input and output values for each workstation are collected from the research paper and it is altered accordingly to the study by reviewing it from the Volvo experts through digital interviews.

Table 4.1: Component list of truck engine[12]

Main components	Materials	Weight(kg)
Cylinder block	Cast iron	260.00
Cylinder head	Cast iron	93.60
Crankshaft	Alloy steel	103
Connecting rod	Alloy steel	21.10
Camshaft	Alloy steel	11.25
Valve	Alloy steel	2.10
Tappet	Alloy steel	3.15
Injector	Alloy steel	2.22
Injector pump	Cast aluminum	9.65
Compressor	Alloy steel	19.40
Turbocharger	Cast aluminum	20.0
Gear chamber	Cast iron	22.1
Flywheel	Cast iron	43.65
Oil pan	Steel	9.35
Intake pipe	Cast aluminum	8
Exhaust pipe	Cast iron	21.5
Alternator	Cast aluminum	6.25

- Disassembly

  When the engine entered the disassembly process it contained all the components listed in Table 4.1. The parts of the engine are disassembled and each component is evaluated. The material inputs for the disassembly process constitute the main components of an engine represented in Table 4.1. The parts such as cylinder head, cylinder block, crankshaft, connecting rod, and camshaft are considered as the highest priority in this process because these are the most common worn components and commonly remanufactured. The remaining components are sent for recycling and those are replaced with the new ones in the reassembly process. The inputs and outputs of the disassem-

bly process considered for the LCA study are presented in Table 4.2
.

Table 4.2: Input and output at disassembly station

Inputs	
Electricity consumption	28 KWh
Water	20 kg
Compressed air	20 m^3
Kerosene	18kg
Engine parts	653 kg
Outputs	
Scrap	167.22 kg
Remanufacturable parts	489 kg

- Burning

This process helps to accomplish the disassembly process completely, components that are not possible to disassemble in the previous station are sent here and it can be removed from the core after burning the components. The output of this process is the components that possess the remanufacturing ability and the components that do not possess the remanufacturing ability considered as scrap for recycling.

Table 4.3: Input and output at Burning station

Inputs	
Electricity consumption	35 KWh
Engine parts	489 kg
Outputs	
Scrap	21 kg
Remanufacturable parts	468 kg

- Washing

The components after the burning process will be received at the washing station. The components are thoroughly cleaned and sanded to perform machining. The output of this process mainly includes the crankshaft, cylinder head, cylinder block, connecting rod, and camshaft. These are the main components that are refurbished at the remanufacturing plant.

Table 4.4: Input and output at Washing station

Inputs	
Electricity consumption	28 KWh
Water	20 kg
Engine parts	468 kg
Outputs	
Remanufacturable parts	468 kg

- Machining

  Washed components, mainly crankshaft, camshaft, cylinder head, cylinder block, and connecting rod received from the washing station are machined.

Table 4.5: Input and output at Machining station

Inputs	
Electricity consumption	64.72 KWh
Water	9 kg
Kerosene	2 kg
Engine parts	468 kg
Outputs	
Remanufacturable parts	468 kg

- Reassembly

  Remanufactured components that are machined in the previous station and the original manufactured components required for the assembly of an engine are sent to the reassembly station. The worn parts sent for recycling in the disassembly station are replaced with the new ones in the reassembly process. After engine reassembly, it will be transferred to the quality inspection.

Table 4.6: Input and output at Reassembly station

Inputs	
Electricity consumption	180 KWh
New parts	185.62 kg
Engine parts	468 kg
Outputs	
Remanufacturable parts	653 kg

- Quality and packing

  After assuring the engine performance that is equivalent to the original manufactured engine, the components are packed and delivered.

Table 4.7: Input and output at Quality and packing station

Inputs	
Electricity consumption	4 KWh
Diesel	6 kg
Engine parts	653 kg
Outputs	
Remanufacturable parts	653 kg

4.1.2.2 Inputs and outputs flow in tool

The inputs and outputs values of each workstation are transferred into the LCA tool (OpenLCA). The material flows correspond to the engine components, and the inputs and outputs flow of the disassembly station that considered in the tool are mentioned in Appendix A. In a similar way, the inputs and outputs of each workstation are selected in the tool. The selected input and output flows in the Openlca tool are all imported from the database Ecoinvent 3.6 providing the various options respect to the geographical boundaries.

The material flow in the LCA tool is selected based on the materials used mainly to manufacture the components of an engine. There are various providers available to provide the information related to those selected material flow, but in this study, the provider whose data limited only to the boundary of Europe is selected. The list of various providers and the provider that selected for a Cast iron flow in this study is shown in Figure 4.3 (as an example).

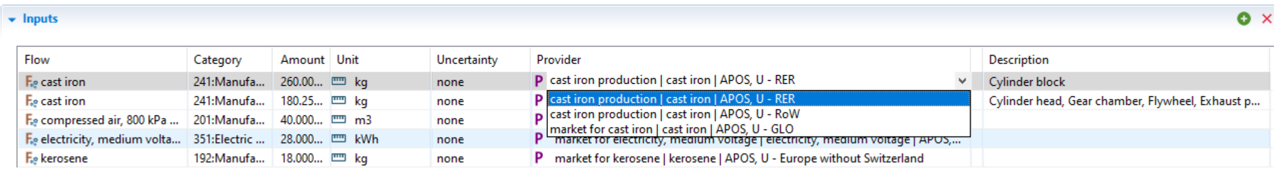


Figure 4.3: Selection of material flow

4.2 Impact category assessment

In this section, the environmental impact score for each impact category is presented. The processes which contribute to the highest impact score are identified and evaluated. The impact scores presented in Table 4.8 are only based on the components that are considered as the main parts of an engine shown in Table 4.1.

Table 4.8: Impact category results

Impact categories	value	Unit
Global Warming Potential 100a	21.0222	kg CO2-Eq
Acidification Potential	0.159	Kg SO2-Eq
Human Toxicity(via air)	1.42580E8	m3
particulate matter formation - PMFP	0.21898	kg PM10-Eq
Marine eutrophication - MEP	0.0387	kg N-Eq
Water depletion - WDP	0.58098	m3

4.2.1 Global warming potential

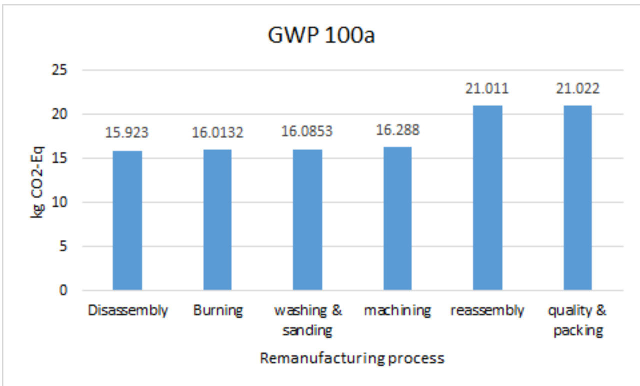


Figure 4.4: GWP of remaunfacturing process

Figure 4.4 shows how every step in the remanufacturing process contributes to the Global warming potential for 100 years on average. It is observed that the reassembly and machining process are the two major contributors to the GWP. The disassembly process is the next major contributor to the impact. Burning, washing, and quality and packing processes are depicting the values of its upstream processes.

The four main flows that contribute to the total GWP of the remanufacturing process are represented in Figure 4.5. Steel flow is considered as the biggest contributor to the GWP and followed by iron and electricity flow. The utilization of steel, iron, and electricity flows is more in the reassembly, machining, and disassembly processes hence these processes exhibit the highest impact scores.

Name	Category	Inventory re...	Impact factor		Impact result	Unit
climate change - GWP 100a					21.02228	kg C...
P steel production, converter, low-alloyed | steel,	241:Manufacture of basic iro...				16.63478	kg C...
P cast iron production | cast iron | APOS, U - RER	241:Manufacture of basic iro...				1.95954	kg C...
P steel production, converter, unalloyed | steel, u	241:Manufacture of basic iro...				1.55271	kg C...
P market for electricity, medium voltage | electri	351:Electric power generation...				0.87525	kg C...

Figure 4.5: Flows contributing to GWP

4.2.2 Acidification potential

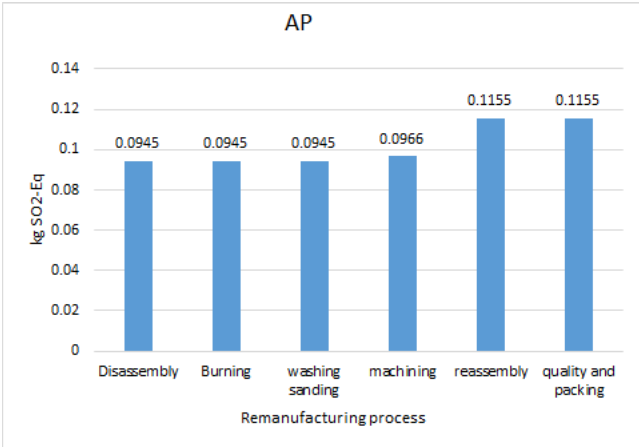


Figure 4.6: AP of the remanufacturing process

Figure 4.6 shows the acidification potential emission at each step of the remanufacturing process. Reassembly and machining are the two major contributors to the impacts. The disassembly process is the next major contributor to the impacts with slightly higher values compared to the machining and reassembly process. Burning, washing, quality and packing includes the upstream impact values of the process.

Name	Category	Inventory re...	Impact factor		Impact result	Unit
environmental impact - acidification					0.11551	kg S...
P cast iron production | cast iron | APOS, U - RER	241:Manufacture of basic iro...				0.11359	kg S...
P steel production, converter, low-alloyed | steel,	241:Manufacture of basic iro...				0.00175	kg S...

Figure 4.7: Flows contributes to AP

Cast iron flow is the major contributor for acidification potential emission at each process shown in Figure 4.7. Steel flow is considered as the second major contributor to the acidification potential even though it possesses a smaller value.

4.2.3 Human Toxicity

Human Toxicity emission at each step of the remanufacturing process is presented in Figure 4.8. Reassembly and machining are the two major contributors to the emission. The disassembly process is the next major contributor to the emission after disassembly and reassembly. Burning, washing, quality and packing includes

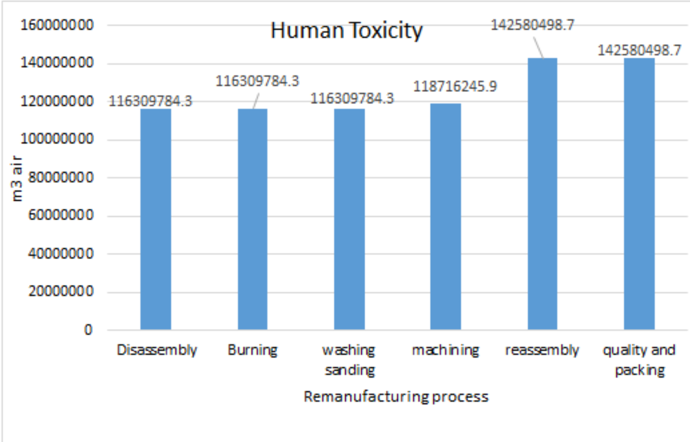
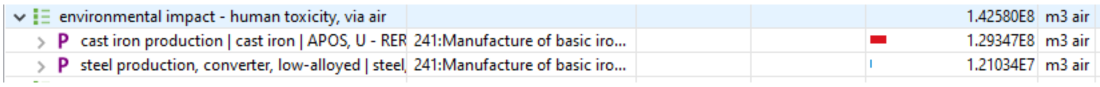


Figure 4.8: Human toxicity of remanufacturing process

the previous upstream values.



environmental impact - human toxicity, via air		1.42580E8	m3 air
P cast iron production | cast iron | APOS, U - RER	241:Manufacture of basic iro...	1.29347E8	m3 air
P steel production, converter, low-alloyed | steel,	241:Manufacture of basic iro...	1.21034E7	m3 air

Figure 4.9: Flows contributing to human toxicity

Two major flows that contribute to Human Toxicity are shown in Figure 4.9. Cast iron flow is the big major contributor to the emission and followed by steel flow.

4.2.4 Particulate matter formation

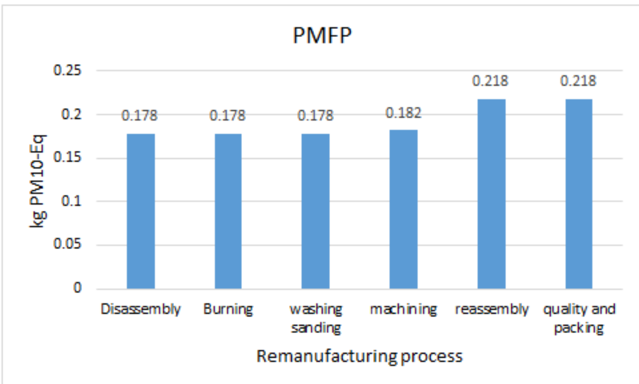


Figure 4.10: PMFP of remanufacturing process

Particulate matter formation at each step of the remanufacturing process is presented in Figure 4.10. Reassembly and machining processes are the two major contributors in forming the particulate matter at the remanufacturing process. The disassembly process is the third major contributor to particulate matter formation.

particulate matter formation - PMFP			0.21898	kg P...
P cast iron production | cast iron | APOS, U - RER	241:Manufacture of basic iro...		0.20797	kg P...
P steel production, converter, low-alloyed | steel,	241:Manufacture of basic iro...		0.01007	kg P...

Figure 4.11: Flows contributing to PMFP

Two major flows that contribute to particulate matter formation in the remanufacturing process are the cast iron flow and steel flow which are shown in Figure 4.11.

4.2.5 Marine eutrophication

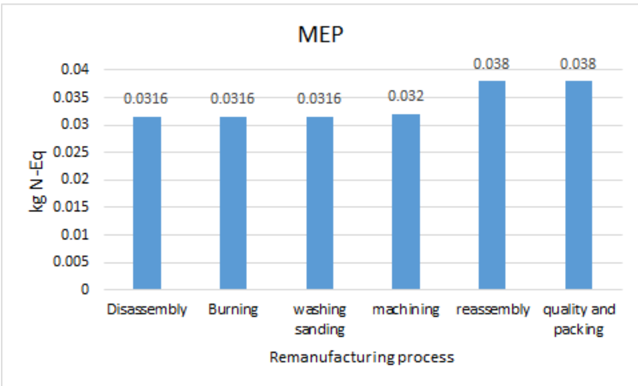


Figure 4.12: MEP of the remanufacturing process

Marine Eutrophication at each step of the remanufacturing process is presented in Figure 4.12. Reassembly and machining processes are the two major contributors to marine eutrophication in the remanufacturing process. The disassembly process is the next major contributor after reassembly and machining. Burning, washing, quality packing includes its previous upstream values in the process.

marine eutrophication - MEP			0.03870	kg N...
P cast iron production | cast iron | APOS, U - RER	241:Manufacture of basic iro...		0.03764	kg N...
P steel production, converter, low-alloyed | steel,	241:Manufacture of basic iro...		0.00097	kg N...

Figure 4.13: Flows contributing to MEP

Two major flows that contribute to Marine Eutrophication are shown in Figure 4.13. Handling cast iron flow and steel flow in the remanufacturing process are the major reasons for the marine eutrophication.

4.2.6 Water Depletion

Water depletion at each step of the remanufacturing process is presented in Figure 4.14. Reassembly and machining processes are the two major contributors followed by washing and disassembly processes to water depletion.

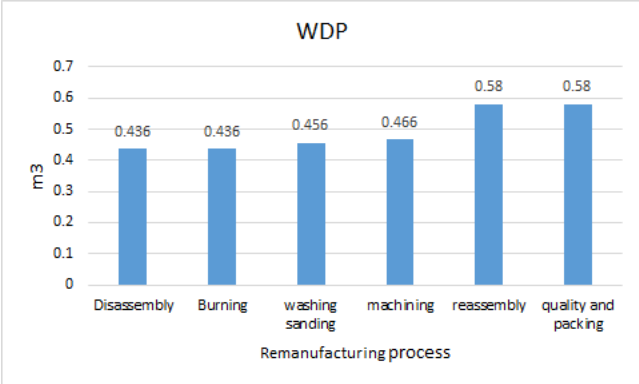


Figure 4.14: WDP of remanufacturing process

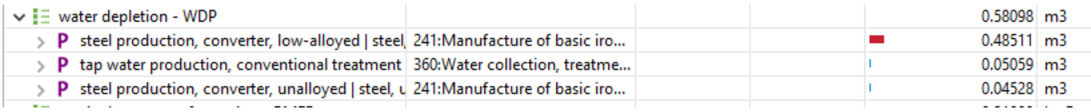


Figure 4.15: Flows contributing to WDP

The flows that provide a major contribution to water depletion are shown in Figure 4.15. The steel flow and water flow in the remanufacturing process is the main contributor to the water depletion.

4.3 Augmented Reality at Disassembly process

One of the main requirements for companies that focus on sustainability in order to prolong the use of product life or parts is to ensure that the remanufacturing process should be cost-effective. The disassembly process is where the various components from the product that can be reused or repaired are retrieved, making it an essential operation in remanufacturing practices. However the disassembly processes require more effort and cost, hence there is a requirement to optimize the operations such that resource utilization both in terms of raw material and manual labor is efficient. The disassembly operations are performed mainly by operators equipped with the necessary power tools and standard instruction manuals. The operators cannot effectively perform their tasks when there are many variants of the product, as there will be various instruction manuals that the operator will have to refer to after identifying the product, thus increasing the cognitive loading of the operator and leading to increase in time to complete the tasks.
Tegeltija, et al. performed an experimental study on implementing AR in a heating circulation pump disassembly process [17]. This study was conducted by comparing two scenarios, scenario 1. Performing manual disassembly with hard copy documentation and scenario 2. Performing disassembly guided by AR. From the implementation of AR at the disassembly observed in the overall improvements in the process. Improvements are characterized as follows [17]

- Reduction in the overall duration of the disassembly process

- The time required for condition analysis of parts is reduced
- Reduction in the time for parts diagnosis
- Time for proper material flow selection of disassembled components is reduced

Considering these improvements to the study, it can be argued that implementing virtual technologies notably like an AR can significantly contribute to eliminating the losses in the current disassembly process technique and to obtain more efficiency. At the disassembly station, the operators provided with cognitive aids such as Augmented reality interaction tools to assist them to perform their tasks efficiently as compared to operators with just hard copies of instruction manuals. With the AR tool, the operator is able to scan the product and identify the different variants of products with ease, along with the identification of the product the AR tools assist the operator by providing specific instruction manuals and component lists to guide the disassembly process. This AR tool eliminates the huge amount of individual instruction manuals and component lists by providing all the essential data on one interface that can be used by the operator, thus improving the process time, quality of performance, and reduced errors. By reducing the errors and performing the tasks correctly the first time there is increased resource efficiency and quality of the products is also improved.

4.3.1 Benifits of implementing AR

Implementing Augmented reality to the remanufacturing process it could potentially eliminate some of the sustainable challenges that are mentioned in the fish-bone diagram Figure 2.2. In the Ishikawa diagram, the problems that affect the environment from the remanufacturing companies are categorized into four types that include employee, machines, materials, and process. By analyzing the benefits of AR implementation at the disassembly process [17], AR possesses that potential which significantly eliminates at least one problem in each category mentioned in Figure 4.16. The problems that include lack of procedure, following old technology, lack of sorting of materials, and energy loss at respective categories can be certainly avoided/eliminated after implementing AR and providing beneficiary results.

From case study at Volvo, the main problem that the implementation of AR will help eliminate is the lack of procedure and old technologies. This is due to the fact that many variants of the engine are disassembled and each comes with their own set of work instructions which increases the complexity of the operation. Currently, the work instructions at the workstation are paper-based and the procedures followed by the operator are based on their personal experience of performing the task for years. With the integration of AR which is connected to the Product Life cycle Management system, the work instructions will be specific to the build of the engine and easily accessible to the operator in a handheld device, which eliminates the requirement for a large number of paper-based procedures. It will also help in assisting new operators or trainees stationed at the disassembly station and not rely on just one operator with experience.

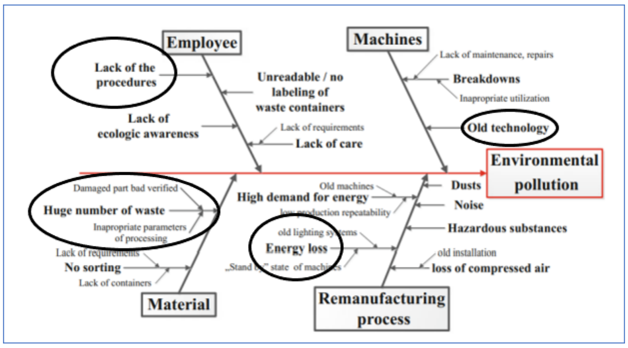


Figure 4.16: Problems eliminated by implementing AR

Moreover, following the right procedure helps reduce the errors, improve the quality of work and better utilization of resources. The parts will be in better condition and are not likely to get damaged during the disassembly as the parts are disassembled correctly, there will be an increase in the number of components that can be reused for the remanufacturing process instead of scrapping these damaged parts and buying new components thus reducing waste and resources. Also, with the proper procedures being followed, this eliminates the repetitive work or redoing tasks due to errors made which reduces the energy consumption at every station.

5
Discussion

Considering all impact categories, the impact values at the reassembly and machining stations are higher than the other workstations. One of the reasons for exhibiting the highest impact values at the reassembly and machining process is, as it includes the impact values of its upstream processes. Since the remanufacturing process begins with disassembling the products, the upstream value is generated at the disassembly station. The impact value created at the disassembly station is crucial to the other processes since the values created here are directly proportional to the other station impact values. The other reason for the higher impact assessment values at the reassembly station is due to the tasks performed at the station, old and damaged parts are replaced with new parts which are mainly made from cast iron and steel, which increases the use of cast iron and steel flows in the system, these are the major flows that contribute more for all types of impact categories, as mentioned in the Figure 4.7, 4.9, 4.13, 4.11, 4.15. Currently, At the remanufacturing plant, the damaged or worn out parts of an engine are replaced by newly manufactured components instead of machining and or reusing parts from another similar engine, this increases the use of new components at the reassembly station and increases resource consumption. If parts from other old engines are used to remanufacture one engine, there will be a reduction in the cast iron and steel flow consumption that contributes to reducing all types of impact categories mentioned in Chapter 2.5.1.2.

Flows contributing to the environment.
Cast iron and steel flows are the two major contributors to all types of impact categories. The usage of the cast iron and steel flow is high in the system due to the components that are considered as the main parts of the engine is mainly made up of cast iron and steel. The main components of the engine are the major contributors for the engine in its weight and cost. The emissions caused by the cast iron and steel flows could not be directly controlled by the company, because the major emission obtained here is during the production phase. However, with the less utilization of the new components of engines made up of cast iron and steel, it can be possibly reduced.

Contribution of AR to the environment.
By implementing AR, significantly reduces human operations errors and assists the operators to perform the tasks correctly for the first time, this results in increased resource efficiency and improving the quality of the products. By reducing repetitive work and errors with proper work instructions, the electricity consumption by ma-

chines used could be reduced. Since electricity flow is one of the major contributors to the GWP mentioned in Figure 8, reduced electricity usage can directly contribute to reducing the GWP of the process.

5.0.1 Results sources and credibility

In an open LCA platform, to obtain the desired results, the database which already existed in the system is downloaded for the study. Even though with adopting the updated database for the study it is impossible to obtain the input flows that perfectly match the real production system. Standard input flow considering the material usage at the real production process is considered as the input to the system. In this study, the collection of the production data regarding the remanufacturing process was difficult due to certain limitations. All the data related to the production process are gathered through literature papers and validated through the interviews with the company personnel. The collected data are altered accordingly to match the real production system.

6
Conclusion

The AR implementation at the disassembly process in the remanufacturing system is the beginning of reaching more sustainable benefits. The experimental studies mentioned in the research papers[17] [5] mentions that AR certainly benefits the process to eliminate the problems related to the time and quality of the processes. From the LCA study, it is also clear that AR could potentially reduce electricity consumption at the process and thus contributes to the reduction of GWP emission in the process. By delivering the detailed work instructions with AR, the probability of damaging the products due to the improper handling can be reduced. This will extend the life of the products and reusability option making the process sustainable by avoiding the usage of new components. By implementing the AR at the disassembly process potentially gives beneficiary results, however certain factors like cost implementation, workers convenience, and educating workers should be considered. Bottani Vignali, A case study from the AR application leads to an increase in employee training time by 20% [29]. In summary, in order to obtain the higher beneficiary sustainable results from the remanufacturing process, the percentage of remanufacturing ability of the products should be increased. More the intake of new components leads to lesser sustainable benefits.

From the factory visits at Flen, it was observed that the crankshafts were always replaced by a newly manufactured rather than reusing a crankshaft, as it was considered cost-effective to purchase a new crankshaft than to machine and use a remanufactured crankshaft. However, using newly manufactured components results in the consumption of raw materials and energy, making the entire remanufacturing process less sustainable.

Furthermore, a case study from the remanufacturing of an engine with advanced restored technologies [12], explained that using advanced restoring technologies for repairing the worn products in remanufacturing over traditional repairing processes, offers certain environmental benefits. In an engine remanufacturing plant in China, advanced restoring technologies such as brush electroplating, arc spraying, and laser cladding are replaced over a traditional machining repairing process and recorded various environmental benefits. The main environmental benefits include a great reduction of ADP by 36% followed by AP, GWP, PED, and EP which reduced by 14%, 15%, 15%, and 13% when compared to the traditional repairing methods [12]. However, it has some drawbacks of consuming more water, materials, energy, and generating pollutant emissions compared to the traditional method.

6.1 Further studies

This study is mainly focused on the environmental assessment of the remanufacturing process and the environmental benefits of the AR implementation. The other two sustainable factors such as economic, and social can also be used for assessment to obtain sustainable results. Therefore a comprehensive approach of sustainable assessment that include all three categories can be examined. However, considering the benefits of AR, it is also considered as expensive to implement in the manufacturing sectors. Therefore, an economic assessment of the AR implementation related to cost and savings can be examined in the future. Due to the lack of time, the sustainable assessment of AR after implementation cannot be examined, a sustainable assessment of AR after implementation can be considered as a future research study.

6.2 Other recommendation Tools for environment assessment

The sustainable assessment of the manufacturing process helps the decision-makers to improve sustainable performance when optimizing the process, design, organization for a higher sustainable level. Since Volvo remanufacturing plant, Flen, is shifting its remanufacturing site to another location with optimizing the process by implementing AR, the following sustainable assessment tools will benefit the company to assess their sustainability performance and improve the sustainability value.

6.2.1 The OECD (2011) tool kit [10].

This tool is taken into consideration as this mainly focused on the environmental assessment at the process level. The OECD sustainable assessment framework provides 18 quantitative environmental indicators to assess sustainability in the manufacturing process. This assessment is a repetitive approach that aims to qualify innovation and continuous improvement of sustainability in manufacturing. Figure 6.1 represents the OECD indicators of environmental assessment.
The indicators are divided into three categories:

- Input indicators I, indicators to assess the inputs of the process which are considered as the main contributors to the environment.
- Operation indicators O, to assess the processes that contribute to the environment in converting inputs to outputs.
- Product indicators P, are the indicators to measure the environmental impact of that product.

With the adoption of the OECD toolkit, several sustainable manufacturing indicators can be assessed. OECD indicators categorizing into the sustainable manufacturing indicators are presented in Figure 6.2. With measuring the remanufacturing process by sustainable manufacturing indicators of OECD, the indicators causing

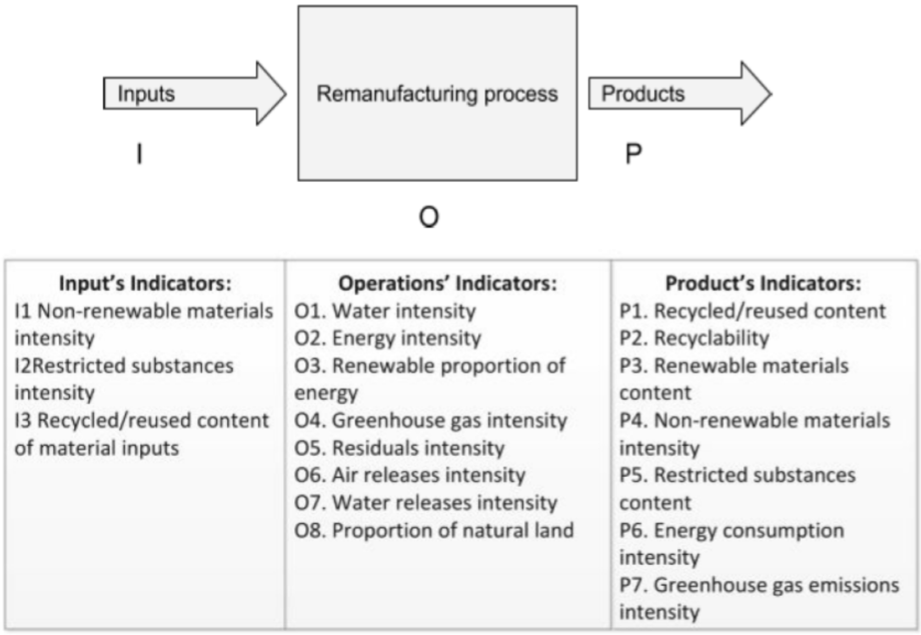


Figure 6.1: OECD sustainable indicators [10]

Remanufacturing process indicators	Corresponding OECD sustainable manufacturing indicators
Materials recovery rate (MRR)	I3, P1, P2, P3
Non-renewable materials rate (1-MRR)	I1, P4
Restricted substances intensity	I2, P5,
Energy intensity	O2,
Portion of renewable energy	O3
Air emissions intensity	O4, O6, P7
Water intensity	O1
Land use intensity	O8
Sewage intensity	O7
Waste generation intensity	O5

Figure 6.2: OECD indicators for sustainable remanufacturing [10]

the highest impact to the environment are identified and improvements can be made to reduce that impact.

6.2.2 Remanufacturing Muda Checklist (RMC) [10].

Muda is a Japanese word that refers to the wastes in the system. This tool helps to identify the factors that contribute to generating Muda and assist the decision-makers in finding potential changes to the system. RMC contains a list of question which gathers the following data [10]:

- Types of Muda (m)- includes the types of Muda that are commonly identified in remanufacturing companies
- Qualifying questions (Q)- includes a list of questions for each type of Muda, which can occur in the remanufacturing companies. It is based on the expert's interview and surveys. Many questions reflect the various situations in the company
- Appearance- if the question matches the current situation of the company, there is a space to provide an answer to that question with having two options: Yes or No
- Priority- priority score can be given to the appeared situation from a scale of 0-4. More about priority scale is described in Figure 6.3
- Sustainability dimension (S)- each question is analyzed from the perspective of a sustainable dimension. This tool covers all three sustainable dimensions of environment, economic, and social aspects (and it is also possible to focus on one particular dimension of sustainability)

P	Description of the importance	Requirements for corrective actions
0	No importance	No
1	Small importance	No
2	Large importance	Yes
3	Very large importance	Yes

Figure 6.3: Priority table for Muda [10]

Figure 6.3 shows how the priority should be considered for the assessment. The priority value from the scale of 0-4 should be given for each answer mentioned in Figure 6.3, where the assigned value (P=2) and (P=3) is considered as the biggest potential improvements. By answering the Questionnaire mentioned in Appendix A, all identified Muda can be analyzed for finding potential improvements. The list of Questionnaires of RMC is presented in Appendix A.

Bibliography

[1] Gunasekara, H., Gamage, J., Punchihewa, H. (2020). Remanufacture for sustainability: Barriers and solutions to promote automotive remanufacturing. Procedia Manufacturing, 43, 606-613. doi: 10.1016/j.promfg.2020.02.146

[2] Ijomah, W., McMahon, C., Hammond, G., Newman, S. (2007). Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development. International Journal Of Production Research, 45(18-19), 4513-4536. doi: 10.1080/00207540701450138

[3] Abbey, J., Meloy, M., Guide, V., Atalay, S. (2014). Remanufactured Products in Closed-Loop Supply Chains for Consumer Goods. Production And Operations Management, 24(3), 488-503. doi: 10.1111/poms.12238

[4] Butzer, S., Schötz, S., Steinhilper, R. (2016). Remanufacturing Process Assessment – A Holistic Approach. Procedia CIRP, 52, 234-238. doi: 10.1016/j.procir.2016.07.066

[5] Gungor, A., Gupta, S. (1999). Issues in environmentally conscious manufacturing and product recovery: a survey. Computers Industrial Engineering, 36(4), 811-853. doi: 10.1016/s0360-8352(99)00167-9

[6] Chang, M., Ong, S., Nee, A. (2017). AR-guided Product Disassembly for Maintenance and Remanufacturing. Procedia CIRP, 61, 299-304. doi: 10.1016/j.procir.2016.11.194

[7] ChangM., Nee, A., Ong, S. (2020). Interactive AR-assisted product disassembly sequence planning (ARDIS). International Journal Of Production Research, 1-16. doi: 10.1080/00207543.2020.1730462

[8] (2020). Retrieved 14 May 2020, from https://www.volvogroup.com/content/dam/volvo/volvo-group/markets/global/en-en/news/2019/jan/volvo-q4-2018-en-2019-01-30-06-20-18.pdf

[9] care, E., values, O. (2020). Operations. Retrieved 14 May 2020, from https://www.volvotrucks.com/en-en/our-values/environmental-care/operations.html

[10] Golinska-Dawson, P., Kubler, F. (2018). Sustainability in Remanufacturing Operations. Cham: Springer.

[11] Liao, H., Deng, Q., Wang, Y., Guo, S., Ren, Q. (2018). An environmental benefits and costs assessment model for remanufacturing process under quality uncertainty. Journal Of Cleaner Production, 178, 45-58. doi: 10.1016/j.jclepro.2017.12.256

[12] Zheng, H., Li, E., Wang, Y., Shi, P., Xu, B., Yang, S. (2019). Environmental life cycle assessment of remanufactured engines with advanced restoring tech-

nologies. Robotics And Computer-Integrated Manufacturing, 59, 213-221. doi: 10.1016/j.rcim.2019.04.005

[13] Portney, K. E. (2015). Sustainability. ProQuest Ebook Central https://ebookcentral.proquest.com

[14] Franciosi, Chiara, et al. "Measuring Maintenance Impacts on Sustainability of Manufacturing Industries: from a Systematic Literature Review to a Framework Proposal." Journal of Cleaner Production, vol. 260, 2020, p. 121065., doi:10.1016/j.jclepro.2020.121065.

[15] Kanchana Sethanan1, Rapeepan Pitakaso2, Monika Kosacka-Olejnik3, Karolina Werner-Lewandowska3, Aneta Wasyniak4 (2019). Remanufacturing sustainability indicators: A study on diesel particulate filter. Logforum 15 (3), 9. DOI: 10.17270/J.LOG.2019.349

[16] Golinska P., 2014, The lean approach for improvement of the sustainability of a remanufacturing process. LogForum 10 (3), 285-293.

[17] Tegeltija, S., Lazarevic, M., Stankovski, S., Cosic, I., Todorovic, V., Ostojic, G. (2016). Heating circulation pump disassembly process improved with augmented reality. Thermal Science, 20(suppl. 2), 611-622. doi: 10.2298/tsci150927043t

[18] Farkhatdinov, I., Ryu, J. (2009). Development of Educational System for Automotive Engineering based on Augmented Reality. _brochure_en.pdf?rev=5a25f7eac825492e92af6343dbf5bc6b

[19] Klopffer Walter, Grahl, B. (2014). Life Cycle Assessment (Lca) A guide to best practice. Weinheim: Wiley-VCH.

[20] Widheden, J., Ringström, E. (2007). Life Cycle Assessment. Handbook for Cleaning/Decontamination of Surfaces, 695-720. doi:10.1016/b978-044451664-0/50021-8

[21] ChaiMay, C. (2019, April 16). Life Cycle Assessment: an Introduction to Concepts and Applications. Retrieved from https://www.azocleantech.com/article.aspx?ArticleID=516

[22] Pennington, D., Chomkhamsri, K., Pant, R., Wolf, M., Bidoglio, G., Kögler, K. et al. (2010). ILCD Handbook Public Consultation Workshop. The International Journal Of Life Cycle Assessment, 15(3), 231-237. doi: 10.1007/s11367-009-0149-6

[23] Kellens, K. (2013). Energy and Resource Efficient Manufacturing - Unit Process Analysis and Optimisation (Energie- en grondstofefficiënt produceren - Analyse en optimalisatie van productiemachines).

[24] Environmental Impacts. (2020, April 30). Retrieved from https://circularecology.com/environmental-impacts.html

[25] Schirone, M., Volkova, A. (2019. Lecture at Chalmers University of Technology (2019-04-03). Sign In. (2020). Retrieved 18 May 2020, from https://pingpong.chalmers.se/courseId/10540/node.do?id=5263630ts=1554307065573u=629167

[26] Andersson, Karin, et al. Shipping and the Environment Improving Environmental Performance in Marine Transportation. Springer Berlin, 2018.

[27] Jia, L., Chu, J., Ma, L., Qi, X., Kumar, A. (2019). Life Cycle Assessment of Plywood Manufacturing Process in China. International Journal of Environmental Research and Public Health, 16(11),

2037. doi: 10.3390/ijerph16112037 http://aos.ro/editura/analeleaosr/annals-on-engineering/archive/vol-9-no-1-2017-annals-series-on-engineering-sciences
[28] Augmented Reality (AR) applications in industries - where it can be useful. (n.d.). Retrieved from http://spectralapplications.com/applications/
[29] Bottani, E., amp; Vignali, G. (2019). Augmented reality technology in the manufacturing industry: A review of the last decade. IISE Transactions, 51(3), 284-310. doi:10.1080/24725854.2018.1493244

A
Appendix 1

Muda (m)	Qualifying question	Appearance		Priority (0–3)	Sustainability
		No	Yes		
Overproduction	1. Lack of production planning				ECON
	2. Production plans/task for workers are often changed				ECON
	3. Long refitting time				ECON
	4. Processing available cores irrespective of the demand				ECON
	5. Overcapacity				ECON
	6. Unbalanced production flow (e.g. different daily standards for workplaces)				ECON
	7. Increasing inventory				ECON, ECO
	8. Breakdowns				ECON, ECO
	9. Remanufacturing defects				ECON, ECO
Inventories	1. There is not enough place for waste				ECON, ECO
	2. Product inventory/WIP partially block the passage of the workplace				SOC
	3. Store new/regenerated parts in the workplace in an amount greater than the current needs (for example. the daily production)				SOC, ECON
	4. There are formed bottlenecks during waiting for documents/decisions/materials processing				ECON, SOC
	5. Lack of place for stored parts				ECON, ECO
	6. Waste are stored on the workplace				ECON, ECO
	7. There is not enough space for waste				ECON, ECO
	8. Cores are bought irrespective of the demand				ECON
Waiting	1. Waiting for the machine (e.g. dryer)				ECON, SOC
	2. Waiting for information/instructions from superiors/staff from other positions				ECON, SOC
	3. Waiting for the material from previous workplace				ECON, SOC
	4. Waiting for tools used by other workers				ECON, SOC

(continued)

Figure A.1: RMC 1

Muda (m)	Qualifying question	Appearance		Priority (0–3)	Sustainability
		No	Yes		
	5. Waiting for the means of transport				ECON, SOC
	6. Absence of workers is high				ECON, SOC
	7. Waiting for parts (new)				ECON, SOC
	8. Waiting for parts (regenerated)				ECON, SOC
	9. Waiting for cores (processed products)				ECON, SOC
	10. Waiting for the parts' picking before the final assembly				ECON
Inappropriate processing	1. Performing more actions than it is required				ECON, ECO
	2. Unclear/lack of customer's specification				ECON
	3. Repeated cleaning of parts				ECON, ECO
	4. Worker makes mistakes during downloading replacement parts (new)				ECON, ECO
	5. Frequent breakdowns of machines				ECON, ECO
	6. Before work, the employee have to get permission from a few departments				SOC, ECON
	7. Processing cores which should be rejected during the pre-selection				ECON, ECO
	8. Lack of procedures				ECO, SOC
	9. Repeating regeneration operations on the same component				ECON, ECO
	10. Wrong order of operations				SOC, ECO, ECON
	11. Too many variants of processed cores				ECO, ECON
	12. Lack of standards for regeneration components (large variety)				ECO, ECON
	13. Several times indexing parts /cores				SOC, ECON, ECO
Transportation	1. Large distance between the workplaces				ECON, SOC
	2. Worker carries material /parts between workstations				ECON, SOC

(continued)

Figure A.2: RMC 2

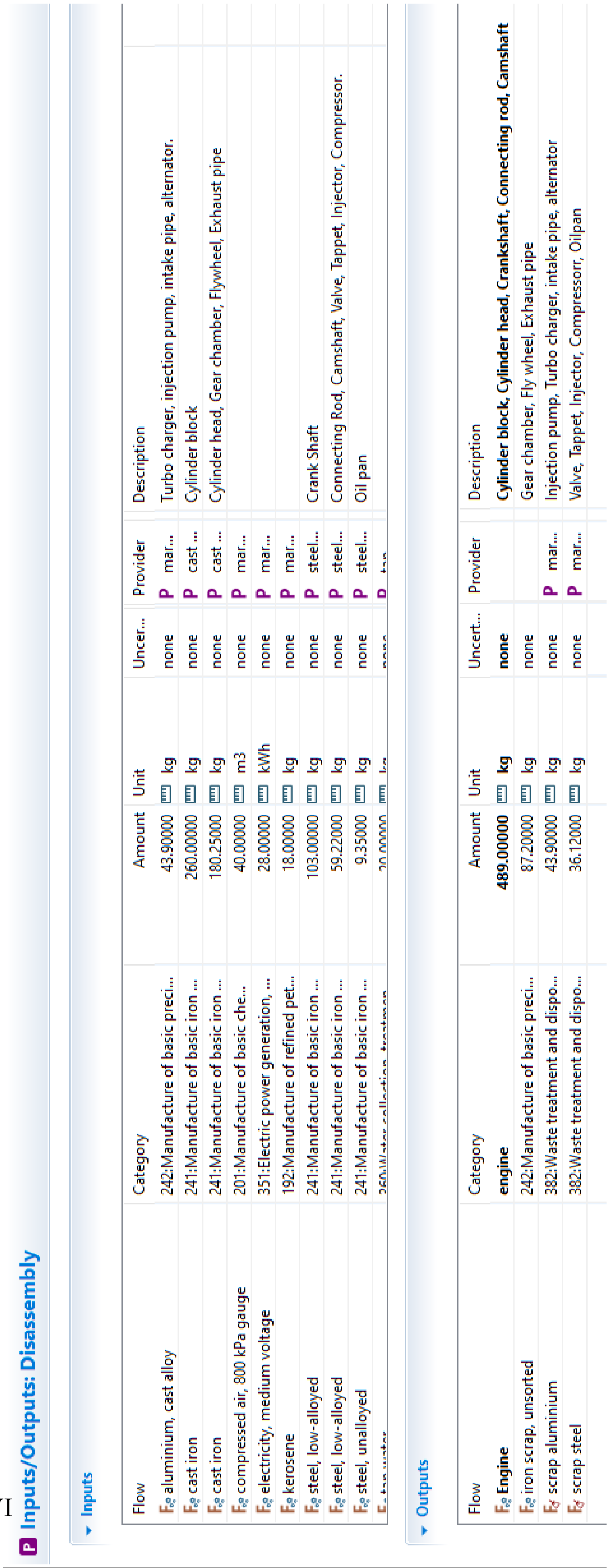
Muda (m)	Qualifying question	Appearance		Priority (0–3)	Sustainability
		No	Yes		
	3. Required repeatedly transport and unloading/loading materials during the work				ECON, SOC, ECO
	4. Subsequent operations are performed at workplaces in different parts of the company				ECON, SOC
	5. Waste containers are located in different parts of the company				ECON, SOC, ECO
	6. The order is divided into too many transport containers				ECON
	7. Many different storage locations of the new and /or regenerated parts				ECON, ECO
Unnecessary motion	1. Looking for tools for realization the basic/remanufacturing process				ECON, SOC
	2. Looking for documents/data				ECON, SOC
	3. Looking for materials/parts at the workplace				ECON, SOC
	4. Frequent stooping during work				SOC
	5. Frequent rotation				SOC
	6. Materials are moved manually between workplaces				ECON, SOC
	7. Work requires considerable physical effort				SOC, ECON
	8. Employee gets on his own material /parts to carry out his work				SOC, ECON
	9. Worker has got in his duties some unnecessary activities				ECON, SOC
	10. Lack of fixed procedures for work				ECON, SOC
	11. Work is carried out mostly in the forced position (standing)				SOC
	12. Too much tools at the workplace				ECON, SOC
	13. Poor technical condition of tools				ECON, SOC
	14. The dispersion of materials /tools				ECON, SOC
	15. Time-consuming cleaning the workplace				

(continued)

Figure A.3: RMC 3

Muda (m)	Qualifying question	Appearance		Priority (0–3)	Sustainability
		No	Yes		
					ECON, SOC, ECO
Defects	1. Damages of materials/products during transport				ECON, ECO
	2. A large number of returns and complaints from customers				ECON, ECO
	3. Inadequate new parts				ECON, ECO
	4. Incomplete cores				ECON, ECO
	5. The problem of identifying cores				ECON
	6. Damages of materials/products during processing				ECON, ECO, SOC
	7. Problems with maintaining the predetermined ratio deficiencies				ECON, ECO
	8. Damaged core				ECON, ECO
Underutilization of employees	1. Employees do not report any improvements				SOC, ECON, ECO
	2. Lack of internal trainings (e.g. in the case of processing unusual product)				SOC, ECON
	3. People report some improvements but they are not implemented				SOC, ECON, ECO
	4. Lack of work instructions				SOC, ECON
	5. Lack of rotation between the workplaces				SOC
	6. Working in excessively burdensome conditions				SOC, ECON, ECO
	7. Unbalanced workplaces				SOC, ECON
	8. Conflicts between co- workers				SOC

Figure A.4: RMC 4



Inputs/Outputs: Disassembly

Inputs

Flow	Category	Amount	Unit	Uncer...	Provider	Description
aluminium, cast alloy	242:Manufacture of basic preci...	43.90000	kg	none	mar...	Turbo charger, injection pump, intake pipe, alternator.
cast iron	241:Manufacture of basic iron ...	260.00000	kg	none	cast ...	Cylinder block
cast iron	241:Manufacture of basic iron ...	180.25000	kg	none	cast ...	Cylinder head, Gear chamber, Flywheel, Exhaust pipe
compressed air, 800 kPa gauge	201:Manufacture of basic che...	40.00000	m3	none	mar...	
electricity, medium voltage	351:Electric power generation, ...	28.00000	kWh	none	mar...	
kerosene	192:Manufacture of refined pet...	18.00000	kg	none	mar...	
steel, low-alloyed	241:Manufacture of basic iron ...	103.00000	kg	none	steel...	Crank Shaft
steel, low-alloyed	241:Manufacture of basic iron ...	59.22000	kg	none	steel...	Connecting Rod, Camshaft, Valve, Tappet, Injector, Compressor.
steel, unalloyed	241:Manufacture of basic iron ...	9.35000	kg	none	steel...	Oil pan
tap water	360:Water collection, treatmen	20.00000	kg	none	tap...	

Outputs

Flow	Category	Amount	Unit	Uncert...	Provider	Description
Engine	**engine**	**489.00000**	**kg**	**none**		**Cylinder block, Cylinder head, Crankshaft, Connecting rod, Camshaft**
iron scrap, unsorted	242:Manufacture of basic preci...	87.20000	kg	none		Gear chamber, Fly wheel, Exhaust pipe
scrap aluminium	382:Waste treatment and dispo...	43.90000	kg	none	mar...	Injection pump, Turbo charger, intake pipe, alternator
scrap steel	382:Waste treatment and dispo...	36.12000	kg	none	mar...	Valve, Tappet, Injector, Compressorr, Oilpan

Figure A.5: input and output flows of disassembly station