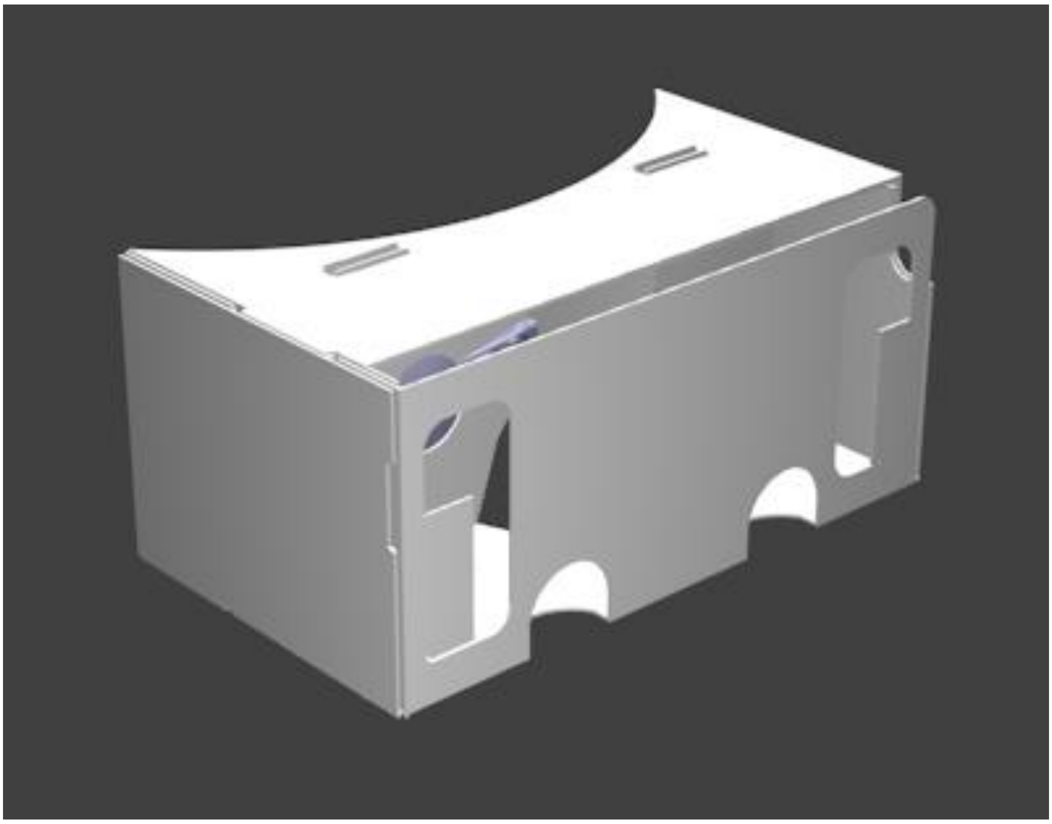

Sustainable Production and Digitalization
An Environmental Assessment of a Smart Factory and a Literature Review of Sustainable Digitalization

Master's thesis in Industrial Ecology

THERESE ADRIANSSON
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Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2017

REPORT NO. 2017:02

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Cover:
A pair of VR glasses, see p. 3-8 for more information.

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SUMMARY
This master thesis is one part of a larger project called Smart Factories. The overall aim with Smart Factories is to create a platform that can be used to spread knowledge about digitalization of industries and to increase the attractiveness for young adults to work in such industries. The project will generate a demonstrator of a digitalized factory that will be exhibited at the science center Universeum. The factory will produce VR glasses made out of corrugated paper and PMMA.

This master thesis looks quantitatively at the environmental impact of the factory. It also includes a literature review about sustainable digitalization. The purpose of this thesis is thus divided into two parts, where the first one is to suggest improvements for the digitalized factory so as the environmental impact is reduced. The second part is to initiate a literature review of sustainable digitalization in order to identify topics for future studies. The purpose of the study is broken down into three objectives:

- Identify five critical areas of the factory
- Identify possible improvements of the factory
- Identify to what extent the topic of sustainable digitalization is covered by scientific literature

LCA is used in this master thesis to a large extent. The result from the analysis is that the five critical areas are the corrugated paper sheets, lenses, racks, rotation press and Eton Systems transporter. It was found that the largest reduction of the environmental impact can be obtained when the amount of consumables is decreased. Additionally, the environmental impact can be significantly reduced if recycled materials are used instead of virgin materials for the corrugated paper sheets and the racks. The production volumes and type of materials are thus important for the project managers to consider.

The literature review show that it is relatively difficult to find reports about sustainable digitalization. Most of the covered reports touch upon the economic and social dimensions of sustainability and less focus is on the environmental dimension. More research is needed on some specific topics, highlighted by the authors of the reports covered in the literature review.

Keywords: Smart Factories, VR glasses, Digitalization, Life cycle assessment

Acknowledgement

This master thesis was the final part of our education at Chalmers University of Technology. It was performed during the spring of 2017 at Swerea IVF in cooperation with Gothenburg Technical College and Chalmers University of Technology.

We would like to give our deepest gratitude to Ulrika Lundqvist who acted as a supervisor and examiner at Chalmers University of Technology. Without her assistance, the quality of our work would not have reached its current standard. Our supervisors at Swerea IVF, Karin Wilson and Jutta Hildenbrand, contributed to new insight and knowledge during the whole master thesis, which is why we would like to give a sincerely thanks to them as well. We would also like to thank Richard Hedman at Gothenburg Technical College who supported our work with practical information.

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Therese Adriansson and Rebecca Hansson
Göteborg, 2017

Table of content

1. Introduction

1.1 Background

The world is facing a rapid digitalization. For industries in Sweden it is essential to keep up with this digitalization in order to maintain the competitiveness on the market. As a consequence of this, the Swedish government has presented a new strategy for the industrialization in Sweden, called Smart Industry (Regeringskansliet, 2015). This strategy has given rise to several projects on the topic. An example of such a project is *Digital lärplattform för den smarta digitala fabriken* (edig), which is run by Swerea IVF and part of an assignment given to *Vinnova* by the Swedish government (Swerea IVF, 2017). Another project, *Smart Factories*, that is coordinated in relation to edig is run by GTC and financed by, for example, *Västra Götalandsregionen* (VGR) (Smarta Fabriker, 2017).

There are a lot of different actors involved in Smart Factories where the main actors are VGR, *Universeum*, Chalmers University of Technology, *Balthazar*, *University of Skövde* and GTC. Additionally, there are 40 other partners involved, such as *Swerea IVF* (Smarta Fabriker, 2017).

As a major part of Smart Factories, there are in total 10 master theses and some additional student projects on different education levels that together contributes to various parts of the project. The students performing master theses originates from Chalmers University of Technology whereas the other students involved comes from, for example, GTC and Yrgo (Smarta Fabriker, 2017).

The aim of Smart Factories is to create a platform that can be used to spread knowledge about digitalization of industries as well as increasing the willingness of young adults to work within such industries. That is of importance since studies have shown that there might be a lack of employees with suitable education in the future (Smarta Fabriker, 2017).

The project will generate two demonstrators (i.e. small digitalized factories) that will be exhibited at two different science centers, namely Universeum in Göteborg and Balthazar in Skövde. The visitors, ages ranging from children to adults, will be able to visually follow the production of a pair of virtual reality (VR) glasses and thereafter use them (Smarta Fabriker, 2017).

The factory should be a so called *smart* factory, which can be defined in various ways. Two examples are that it should include the latest developed technology and be connected to the internet. It is thereby possible to overview the factory from, for example, smartphones and computers. A smart factory is a factory that serves as an attractive workplace and increases the competitiveness on the market (Bengtsson, 2016). In order to ensure that these types of factories fit into a digitalized future, it is suitable if considerations are taken on its sustainability since there is a high awareness of sustainable development in the society today.

This master thesis is part of Smart Factories and edig. It asses the environmental performance of the demonstrator at Universeum, partly by using a Life Cycle Assessment (LCA), which means that the environmental dimension of sustainable development is covered in a quantitative way. The social and economic dimensions of its sustainability are only highlighted in a qualitative manner.

1.2 Purpose

There are two main purposes of this master thesis, where the first one is to suggest improvements for the digitalized factory that reduces its environmental impact. This will be done by focusing on five processes within the life cycle of a pair of VR glasses that contributes the most to the environmental impact, so called critical areas. The second purpose is to initiate a literature review of sustainable digitalization in order to identify topics that require future studies.

The results from this master thesis will be used during the exhibition at Universeum as a learning opportunity for the visitors. The information will be provided as VR content that the visitors can take part of through their VR glasses and a smartphone. The results will also be used in edig, which was introduced in Section 1. Additionally, the results from this thesis can be used as a basis for further studies and master theses on the topic of sustainable digitalization.

1.3 Objectives

- Which are the five critical areas in the factory based on the following factors: emissions of greenhouse gases (GHGs), depletion of abiotic resources and emissions of other compounds that can give rise to eutrophication, acidification, human- and environmental toxicity, photochemical oxidation and ozone layer depletion?

- Would it be possible to reduce the environmental impact and resource consumption of the critical areas? How can these improvements be performed and to what extent do those reduce the total environmental impact of the factory?

- Identify to what extent the topic of sustainable digitalization is covered by scientific literature. Which topics do the authors of the scientific literature highlight as important and less important? Which topics require further studies?

1.4 Limitations

- The possibility to affect different parameters in the factory are limited because some decisions have already been taken. For example, it is already determined that corrugated paper will be used as a material in the VR glasses.

- The environmental impact caused by personnel in the factory that is not directly connected to the production process itself, such as individual transports to and from work, is excluded in this study. The reason for this is the difficulty to estimate how such parameters might change as industries are becoming more digitalized. It is also assumed that such impacts are the same for a digitalized and conventional factory.

- The environmental impact caused by the waste produced at Universeum and Stora Enso will be included in the study until the waste reaches the recycling plants. What happens during the end of life treatment are not included in this assessment since that lays outside the boundary of what this master thesis can affect.

- The calculations of this master thesis will not be updated if any decisions are taken regarding the layout of the factory after a substantial part of the results are obtained due to time restrictions.

- Any statements on the actual sustainability of the factory will not be made since there are no time to perform similar calculations for a conventional factory and there is thus no reference scenario to compare with.

2. Theory

This section aims to describe some important underlying concepts related to the master thesis. Firstly, a description of the factory at Universeum is presented together with illustrating figures. Thereafter, the concept of digitalization is defined, followed by an explanation of the connection between digitalization and the industry, education and a sustainable society respectively. Lastly, the general framework of an LCA is described as well as a software commonly used for such assessments.

2.1 Description of the factory at Universeum

As mentioned previously, the main purpose of Smart Factories is to build a digitalized factory that aims to spread knowledge about digitalization as well as to increase the interest of technology for different target groups, mainly young adults. This factory will be located at Universeum in Göteborg during the two first years and thereafter moved to Lindholmen at Hisingen. A second factory will be built at Balthazar in Skövde based on the knowledge and insights that the factory at Universeum brings. However, this master thesis only focuses on the factory at Universeum.

The product that the visitor receives from the factory is a pair of VR glasses that can be used by the visitor by inserting their smartphone and activating an application designed specifically for Smart Factories.

The vision is to build a factory where the visitor easily can follow the production process. The production chain of the VR glasses is illustrated in Figure 1.

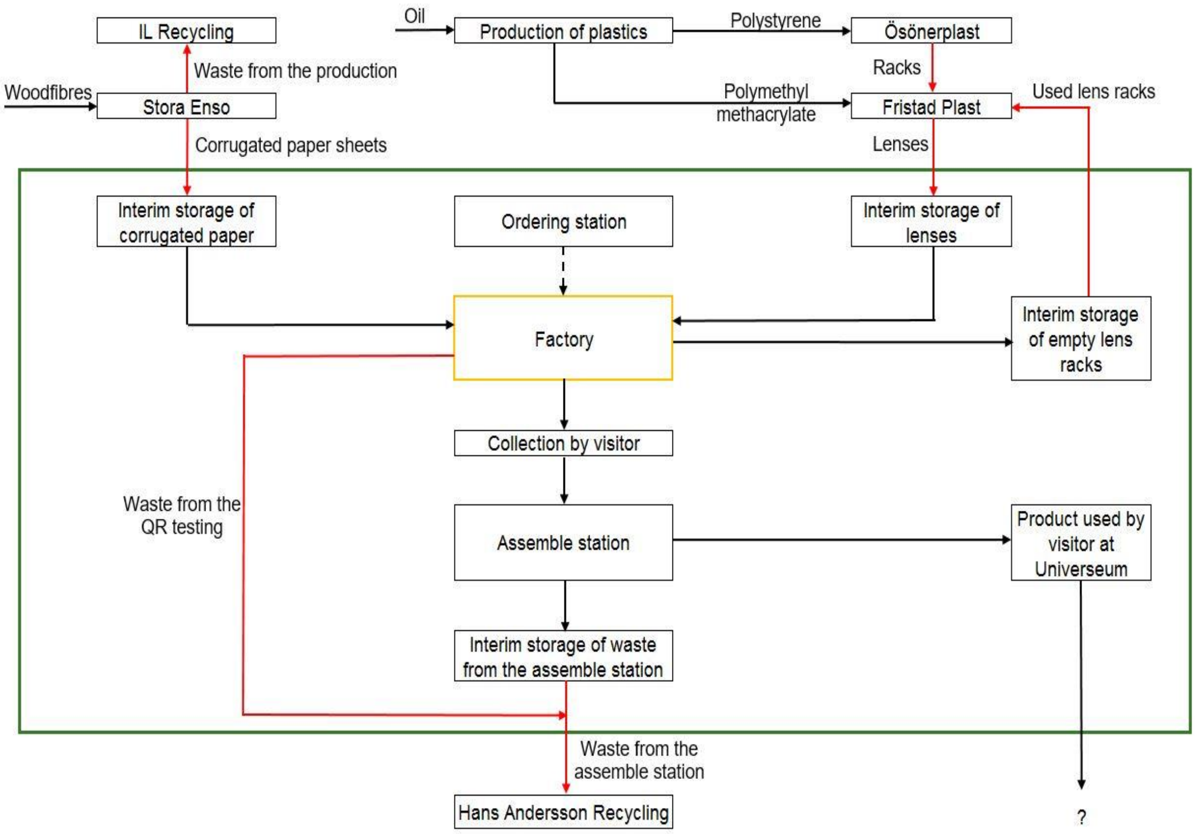

Figure 1. *An overview of the production chain of the VR glasses until the product leaves Universeum. All the solid arrows represent material flows, but the red arrows also illustrate transports accounted for in the study. However, the transports related to the maintenance are excluded in this figure. The dashed arrow represents an informational flow.*

The production process of a pair of VR glasses is described below. Specific information about each step, such as materials used in the components, are excluded from this text and the reader is instead referred to Appendix I.

The main inputs to the factory are lenses, corrugated paper sheets and electricity. The material flows of lenses and corrugated paper sheets are visualized in Figure 1, and are also explained in detail in the sections below. The electricity is, however, not visualized in the figure since it is neither a material flow nor an informational flow. All components in the figure are, to various degree, electricity demanding, which have been included in the study and are further explained in Section 3.1.1.

Corrugated paper sheets are the first main input to the factory and are produced at one of *Stora Enso's* facilities located in Skene, 60 km from Universeum. It is produced from wood that is cultivated and transported to Stora Enso where it undergoes several processing steps to obtain the corrugated paper sheets. All waste that are produced during this production are collected by *IL recycling*. The corrugated paper sheets are thereafter transported by trucks to Universeum.

Lenses are the second main input to the factory and are produced at *Fristad Plast* located 80 km from Göteborg. The lenses are formed with injection moulding into the shape illustrated in Figure 2. The lenses are stored in racks, which are produced at *Ösönerplast* located 60 km from Göteborg. These racks are transported to Fristad Plast where they are filled with 100 lenses in each rack. They are thereafter transported from Fristad Plast by trucks to Universeum. Empty racks are transported back to Fristad Plast for reuse.

Figure 2. *The lenses visualized from two different angles.*

When the corrugated paper sheets and lenses arrives at Universeum, they are stored at an interim storage room before entering the factory since the factory can not store more than a certain amount of corrugated paper sheets and lenses. All the inputs to the factory and the waste produced in connection to the factory at Universeum are stored in these rooms. A more detailed figure on what happens in the factory is illustrated in Figure 3.

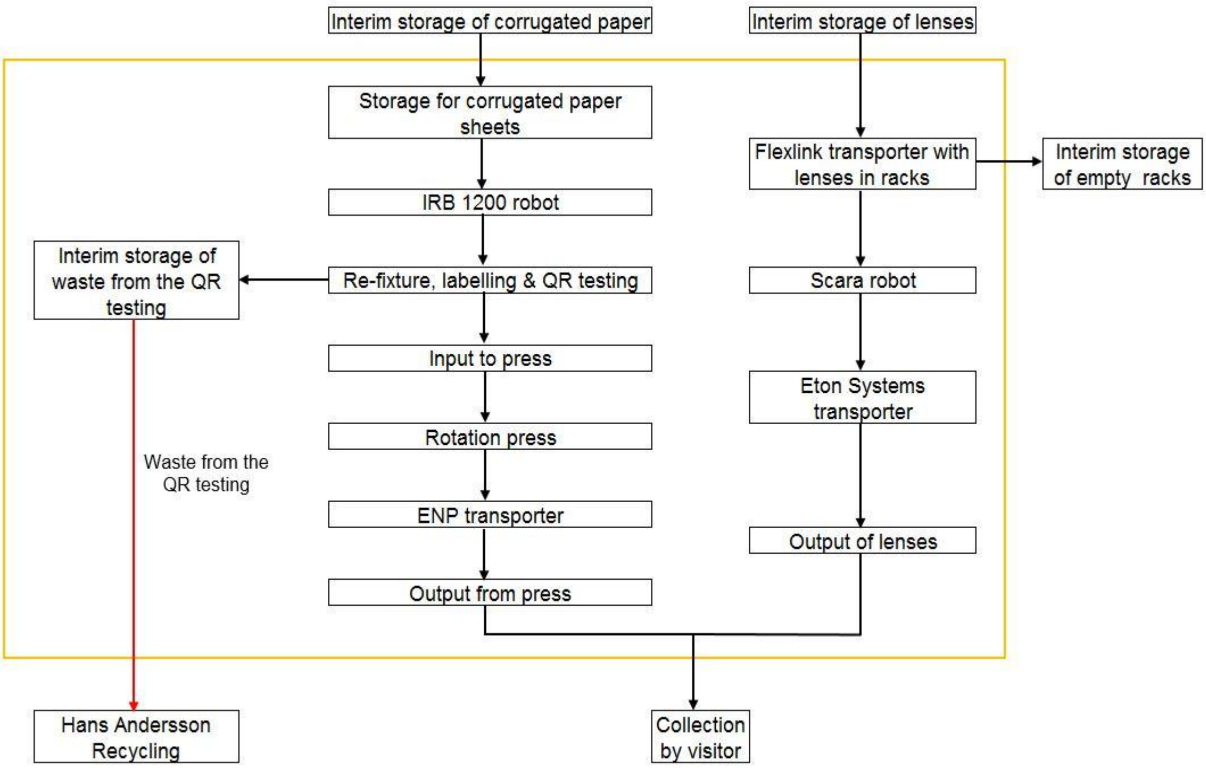

Figure 3. *An overview of the factory, illustrated by the yellow box in Figure 1. All the arrows represent material flows, but the red arrow also represents a transport. The electricity consumption of the factory is not visualized in the figure but is included in the study.*

The production in the factory starts when the visitor order a pair of VR glasses at the ordering station. This station consists of three displays where the visitor order the VR glasses by scanning their tickets. When ordering, the visitors have the opportunity to choose if they want to have a certain text printed on their glasses, such as their names.

The production of the VR glasses consists of two different production lines, where the first one is the production of the pressed corrugated paper sheets and the second is the provisioning of the lenses to the visitor. These lines are monitored by one camera each. The lines are described below respectively.

The first line, the production of the pressed corrugated paper sheets, starts at the storage for the corrugated paper sheets in the factory. The storage consists of 300 corrugated paper sheets in two piles respectively. It is manually re-loaded with corrugated paper sheets from the interim storage room when it is empty.

The next step in this production line is that the corrugated paper sheets are picked up from the storage by an IRB 1200 robot provided by the company *ABB*. The robot has to take a new grip after it has picked up the corrugated paper sheets, which is done by placing the sheets on a re-fixture plate. With the new grip, the robot can take the corrugated paper sheets to the labelling station where ink is used to label the corrugated paper sheets with two Quick Response (QR) codes and with the text chosen by the visitor at the ordering station. The QR codes are thereafter tested by a scanner, and the robot puts the sheets in a waste pile if there is something wrong with the codes.

The printed corrugated paper sheets are thereafter transported into a rotation press on a device called “input to the press” in Figure 3. The rotation press consists of two engines and two different rolls. The idea is that it presses the VR glasses onto the sheets, but due to technical- and safety issues of having an actual press at Universeum this step is simulated and instead the sheets are pre-pressed at Stora Enso. In practice this means that the press located at Universeum only is a set of rotating rolls, without knifes, driven by two engines. However, the factory at Universeum consists of a press anyway in order to make the factory visually look as complete as possible for the visitor.

After the corrugated paper sheets have left the rotation press, it is transported on a transport system provided by the company *ENP* to the part in Figure 3 called “output of the press”, which is the last step in this production line. The output of the press consists of an arm that flips the corrugated paper sheets into a box at which the visitors can collect their sheets.

The second production line in the factory is the provisioning of the lenses, which starts when the visitors scans one of the QR codes printed on the corrugated paper sheets. The production line starts at an oval transport system provided by the company *Flexlink.* The racks are placed on the transport system and transported around the oval track.

The lenses are thereafter picked up by a Scara robot provided by ABB and placed on a holder, which is visualized in the upper part of Figure 2.

The last transport system, provided by the company *Eton Systems*, picks up the lenses from the holder, lower part of Figure 2, and transports the lenses to its output. The lenses falls down through the output and into the hands of the waiting visitors.

After the visitors have collected the corrugated paper sheets and the lenses, the product can be put together at the assemble station that consists of two tables and two displays. The purpose of the displays is to provide information on how to assemble the glasses in a smart way. This information was produced by two other master thesis students involved in Smart Factories.

At the assemble station, the visitors separates the parts of the corrugated paper sheets that will become the actual VR glasses from the rest of the sheets. The shape of the sheet after the separation is illustrated in Figure 4. The parts that become waste contains the second QR code, which is scanned by the visitors in order to make sure that the visitors throws the waste in a correct way. That is of importance since it reduces the volume of the waste, which in turn makes it easier for Universeum to manage. The waste is thereafter collected and stored at Universeum before it is transported to *Hans Andersson Recycling* located in Göteborg.

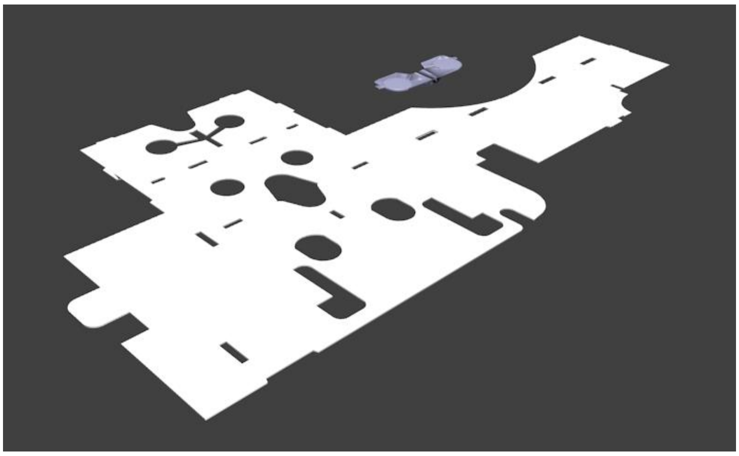

Figure 4. *A pressed corrugated paper sheet where the blue unit is a prototype of a lens (use of figure is approved by Niclas Busck and Fredrik Svensson).*

The final product, assembled by the visitors, is illustrated in Figure 5. The user inserts their mobile phone after downloading a certain application, developed specifically for Smart Factories. This application contains links to VR content, information about the factory and some machine parameters, such as machine health. The application and the VR glasses can be used by the visitor at home, which prolongs its use-phase.

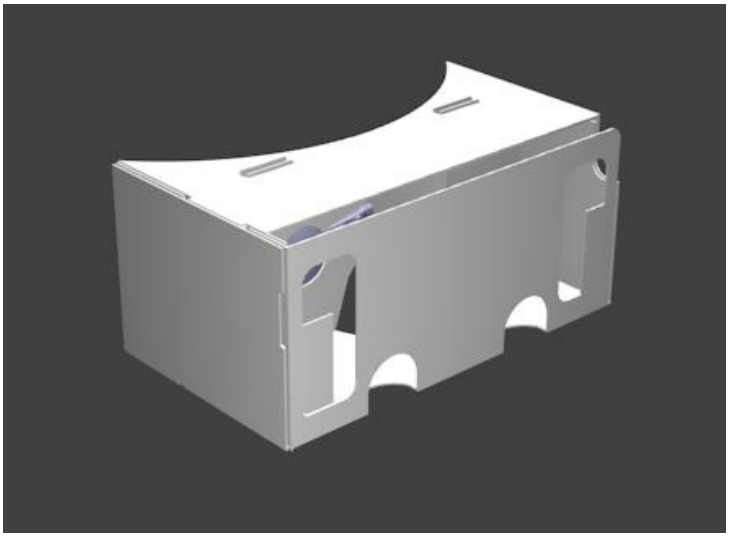

Figure 5. *A pair of VR glasses (use of figure is approved by Niclas Busck and Fredrik Svensson).*

2.2 Digitalization

There has been a rapid digitalization of the industry from the beginning of the 90s until today and it is predicted to continue (Regeringskansliet, 2015). It is therefore important to understand the underlying concept of digitalization. Detailed descriptions about digitalization in different contexts can be seen in the following sections. Firstly, different definitions of digitalization are described, followed by a description about how digitalization affects the industry in Sweden today. Furthermore, the importance of education is explained and lastly follows a description of digitalization in a sustainable society.

2.2.1 Definition

There are mainly two different types of digitalization, one of which is the process of transforming information from being analogue to digital which opens up the opportunity to share information in a completely new way. The digitalized information can, for example, be structured and stored in databases available for people all around the world. This type of digitalization is called *informational digitalization* (Regeringskansliet, 2014).

The second type of digitalization is about the increased use of information technology (IT) in the society and is thus called *societal digitalization*. This type is more difficult to define since it is being increasingly integrated in our life and it is therefore hard to distinguish the evolution of life from the societal digitalization. It does, however, mean that different parts of the society and the world can communicate with each other in new ways. The utilization of technologies originating from the societal digitalization can result in major benefits for companies since it, for example, can increase the productivity of an industry (Regeringskansliet, 2014), as being described in Section 2.2.2.

From this point, the concept of digitalization in this report will refer to the societal digitalization.

2.2.2 Digitalization of the industry

Digitalization affects the industry in many ways. It does, for example, open up a whole new world of opportunities for the products where they can be information carriers (containing for instance sensors and microcomputers). It is, however, not only the products themselves that changes as the industry is becoming more digitalized but also the way of producing them with, for example, more automation. The digitalization of the industry makes it possible for machines, humans and products to communicate with each other, which opens up for smarter products and processes (Teknikföretagen, 2015).

The current digitalization of the industry has a high value for Sweden since it affects the manufacturing industry, which is strongly connected to Sweden’s gross domestic product (GDP), export and employment (one fifth of all jobs in Sweden are within the industry). The manufacturing industry includes several areas, such as the automotive industry and the machine industry, that are affected by digitalization in different magnitude and rate. The automotive industry is one of those areas where digitalization already has made major marks, with for example new ways of developing and selling the vehicles. An area that most likely also will face a major change is the machine industry, but not as quickly as the automotive industry. The change itself is similar between the automotive industry and the machine industry, but one main difference is that the equipment in the machine industry have longer lifetimes which affects the rate of their replacement (Bossen et al., 2016).

Due to the variety of areas within the manufacturing industry, there is not one single solution on how to handle and face digitalization in a simple way. The solutions does, however, contain similar technology areas that most likely are of big importance (Bossen et al., 2016; Teknikföretagen, 2015). Those technology areas are listed below.

- *Simulation and modelling* – Digitalization opens up new ways of exploring products and processes in a virtual environment, which for example can result in more efficient processes.

- *Systems of systems* – The integration of systems, such as those with different life cycles and producers, is a key aspect for the possibility to utilize the benefits of digitalization.

- *Big data-analysis* – Huge amounts of data is a consequence of a digitalized industry, which requires improved methods to be able to analyze it in a manageable way.

- *Wireless communication* – A lot of equipment within the industries as well as the products themselves are becoming increasingly connected, which for example increases their energy use. This means that the energy use has to become more efficient.

- *Cyber security* – Since equipment and products are becoming more connected, it also increases the threat for cyberattacks. Increasing the levels of security against such threats are therefore essential for the industries as they are becoming more digitalized.

- *Smart electronic systems* – As new products are formed, caused by digitalization, their intelligence is increasing. That basically means that the products can absorb information from its surroundings and adapt accordingly.

- *Additive production* – The production of a product directly from its digital model is possible in a digitalized industry, which for example can improve the design of the product.

2.2.3 Education and digitalization

Sweden needs to make sure that the technology areas mentioned above are prioritized in order to digitalize their industries further and thus ensure their competitiveness on the global market. Bossen et al. (2016) suggests several proposals to ensure this. An example of such a proposal is to increase the attractiveness for natural scientific studies in elementary school.

An increased level of knowledge of future employees will be essential when the industries are becoming more digitalized since the jobs in the future are predicted to be more advanced. This requires the future employees to have a higher level of education, in for example engineering, than what is required today for similar assignments. Increasing the attractiveness for this kind of jobs as early as in elementary school are important since most students have low knowledge on which jobs and career possibilities there are on the market and thus needs to be presented in early ages (Teknikföretagen, 2015).

2.2.4 Digitalization in a sustainable society

The ongoing digitalization is not only important for the industry itself as it creates benefits and challenges, but it is also likely to be essential for the survival of human beings as it affects the environment. There are different views on whether digitalization affects the environment in a positive or negative way. However, there are factors that indicates that digitalization is essential for meeting the challenges that the environment is facing. One challenge is the well-known climate change caused by human activities where the two main contributors are the population increase and the economic growth. To handle this issue it is vital that changes are made not only in our life style, such as consumption patterns, but also within the production (Digitaliseringskommissionen, 2016).

According to Digitaliseringskommissionen (2016), the utilization of the technologies originating from the digitalization is considered to play an important role in the solution for climate change. Digitalization can, however, give rise to other issues such as the probable increase in energy demand, which in turn can counteract the carbon dioxide (CO_2) reduction if the energy is produced from fossil resources. It is therefore important to take all aspects into consideration when answering the question to whether digitalization is good or bad for the environment.

One way to categorize the different impacts on the environment is to divide them into three levels: direct effects, enabling effects and system effects (Digitaliseringskommissionen, 2016). These three effects are presented below.

The effects that are most easy to grasp are the *direct effects*, which are basically the positive and negative environmental impacts caused by a product during its life cycle. These effects are thus dependent on many choices made by the producer, such as the choice of materials, energy source and design of the product. Consumers are, however, important for these effects as well since their consumption pattern control how much that is produced (Digitaliseringskommissionen, 2016). This type of effects are the ones in focus in this master thesis.

The second type of effects are the *enabling effects*, which is about the possibility for IT products to reduce the environmental impact caused by different activities. IT can, for example, affect the resource efficiency as well as the product design, which in turn can have a significant effect on the environment in either a positive or negative way (Digitaliseringskommissionen, 2016).

The last type of effects are the *system effects*, which does not include any direct technological factors but rather the change in our behavior which in turn can affect the environment in either a positive or negative way. It is important that the user of a technology understand the product so that the environmental impact can be reduced for the product. There are four different ways that digitalization can give rise to system effects:

- The first one is that it can provide and distribute information, which in turn can be used to make environmentally friendly decisions. One example is that the product can be an electricity meter that shows the current electricity use. The user of the product can from this information actively choose to turn off the lights in a room to reduce their electricity consumption.

- The second way in which digitalization can give rise to system effects is by enable dynamic pricing and enhance price sensitivity. What this means is that the users of IT products can choose to turn off their products when the price of the electricity is high or when the availability of renewable electricity is limited.

- The third way is to develop business models and technology utilization, which in turn can cause changes in the behavior of the users. An example of this is when music is consumed via the internet instead of using physical discs that increases the energy demand when the music is stored on servers (direct effects), but also reduces the resource consumption when less discs and stereos are produced (enabling effects).

- The last way that digitalization can give rise to system effects are as negative effects. Digitalization can affect the environment by triggering rebound effects, which basically means that an increased resource efficiency on a micro level not always gives rise to an increased resource efficiency on a macro level. The most obvious example is the case when digitalization results in reduced price of different products, which in turn causes a higher consumption of that product and thus increases the emissions caused by its production (Digitaliseringskommissionen, 2016).

As can be understood, there is an ocean of factors that have to be considered when answering the question on whether or not digitalization is good for the environment. Additional factors have to be considered when asking the question if digitalization is sustainable or not since that includes social and economic factors as well. Below follows examples of this.

One necessity for digitalization is the availability of affordable electricity. This is something that varies around the world where, for example, most countries in Africa produced less than 100 TWh each in 2015 which can be compared to China that produced more than 3000 TWh during the same year (Enerdata, 2017). The large difference can cause social and economic problems for the countries in Africa, and others with low electricity production, as the digitalization increases since they will fall behind and lose ground on the global market. This is because their productivity can not compete with the digitalized productivity in other countries (European Commission, 2017). As a consequence, this will cause even more fragmentation between developed and developing countries in the world, leading to more inequities (Schoenrock, 2016).

The potentials for small- and medium businesses to grow are huge when the digital economy develops on the market since they can reach global markets and find possible employees from the first day. Adapting to the upcoming digital technologies are thus predicted to play a key role in the future survival for many businesses (European Commission, 2017). Additionally, adapting to the digitalization is essential for a country's competitiveness on the global market and there is thus an economic risk for those countries who fails to do so, as mentioned in Section 2.2.2.

Maintaining, or even increasing, the available jobs on the market is essential and a key aspect to keep in mind as the society are becoming more digitalized. As described in Section 2.2.3, there will be a shift in the characteristics of the jobs as the industries are becoming more digitalized. A lot of the current jobs will be lost due to more automatisation in the industries, but at the same time some argues that there will be an increase in other types of jobs (Teknikföretagen, 2015). For example, studies have shown that approximately half a million jobs were created in the United States (US) as a result of the development of mobile applications. Additionally, it has been shown that companies within countries that have engaged the consumers online have increased their sales rate with 22 % compared to those who were offline. Consequently, it seems to be beneficial to embrace the digitalization from an economic point of view since it can expand businesses and create further jobs (European Commission, 2017).

2.3 Life Cycle Assessment

LCA is a systematic tool that is commonly used in the society today by, for example, industries and non-governmental organizations (NGOs). It is used to assess potential environmental impacts, based on the emissions and resource consumption that a product or service give rise to during its life cycle (Baumann et al., 2004).

The first assessments that applied a life cycle thinking were conducted during the end of the 60s. The focus of these assessments was to look at aspects such as energy consumption, raw material extraction and to some extent the waste handling. The highest priority was assigned to the energy consumption during the first years when the tool was developed, and to some extent also the waste handling, whereas less focus was on evaluating the actual material consumption. This was due to several concerns about the oil crisis in the 70s and debates on whether waste could be a resource or not. The most famous example of an LCA from the late 60s is a study where *Coca Cola* looked at the production of their beverage containers and compared those with other types of containers (Jensen et al., 1997; Baumann et al., 2004).

The whole life cycle of a product or service is not always included in an LCA. How much that is included in the study depends on the purpose of the assessment. Having a *cradle-to-grave* perspective means that the whole life cycle, from raw material extraction to the final waste disposal, is included in the assessment. Another perspective is to include the processes from raw material extraction until the product has been produced, which is called a *cradle-to-gate* perspective. A third perspective of an LCA is where only one value-added process is considered in the assessment which often is referred to as having a *gate-to-gate* perspective (Baumann et al., 2004).

The result from an LCA can be used for different purposes. One example is that it can be used in decision-making processes in the sense that the results from several LCAs, where different policy actions have been assessed, can be compared in order to come up with the most appropriate policy action(s). Another example is to use the result to identify different improvement opportunities in the life cycle (Baumann et al., 2004; Ross et al., 2002).

There are several opinions on whether this tool is useful or not, and to what extent. Some argues that communicating the results obtained from an LCA is challenging because there are differences in the level of understanding of various concepts used, such as global warming potential (GWP). Therefore, it might be difficult for some people to understand the results. Others believe that it is an easy way to compare different alternatives in order to choose a product system that give rise to a lower environmental impact, which can be used by a company in their marketing (Baumann et al., 2004).

2.3.1 Framework of LCA

The ISO standard 14040 provides frameworks and guidelines on how to conduct an LCA. It is provided by a non-governmental organization, The International Organization for Standardization (ISO), that generally provides international standards for products and services. The aim with the international standard is to make sure that products and services are of good quality and safe to use (Baumann et al., 2004). The general framework of an LCA from this standard is illustrated in Figure 6. An overview of what should be included in the different steps is described below.

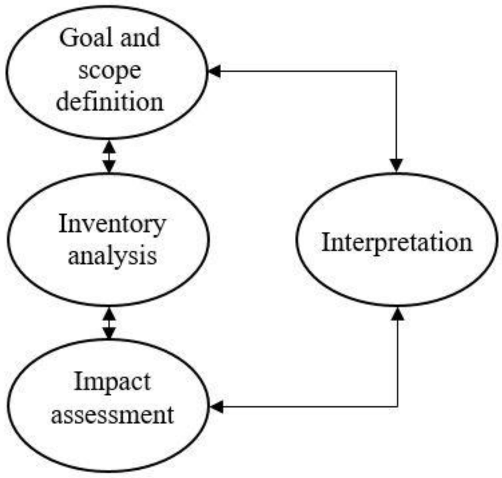

Figure 6. *General procedure for conducting an LCA (illustrated by the authors of this master thesis, inspired by Baumann et al., 2004).*

Goal and scope definition
Defining the goal and scope is the first step in the LCA framework. A well-defined goal definition is important and can be characterized by having clearly stated objectives and purposes (Baumann et al., 2004).

The scope definition consists of several steps. Defining the functional unit (i.e. a unit describing the function of the system) is one of the first steps. It is important that all flows included in the LCA are related to this unit because that makes it possible to compare different products that have the same function. It makes it, for example, possible to compare two water bottles produced from different materials (Baumann et al., 2004).

After the functional unit has been determined, the system boundaries should be described. The boundaries that should be included are according to Baumann et al. (2005):

- Geographic
- Temporal
- Between the technical system and nature
- Production of capital goods
- Between the life cycles of different products

Specifying the geographical boundaries means that all the steps in the life cycle needs to be assigned to a specific geographical area. This will affect the result in the sense that pollutants affect the surrounding environment in various magnitudes and rates in different parts of the world. In addition to this, manufacturing of products and electricity production are examples of processes that can vary a lot in different countries (Baumann et al., 2004).

Emissions occurring over the life cycle of a product might not only give rise to effects in the short term, but also in a longer time perspective. It is therefore important to clearly state whether the LCA is looking at the past, the present or the future. Additionally, it is important to state how far back or forward in time that will be included. The expected lifetime of the product or service is thus of importance for this system boundary (Baumann et al., 2004).

Within the boundary between the technical and natural system, it is important to state where the life cycle starts and ends. In general, when a flow enters or leaves human control, it also enters or leaves the technical system. For example, when minerals are extracted from the ores or oil is pumped up from the ground, it leaves the natural system and thus enter the technical system (Baumann et al., 2004).

When it comes to the system boundary about the capital goods, the time boundary is important to consider. If the aim is to look at the future environmental effects from a present production system, then it is of less interest to look at the environmental impact caused by investments made in the past. Whether or not capital goods are included in the LCA needs to be clearly stated and motivated (Baumann et al., 2004).

Many of the life cycles for different products are clearly interrelated with each other. It is therefore important to determine the boundaries between the different life cycles when conducting an LCA. For example, the end of life treatment for a product might be incineration. However, there are multiple other products that are co-incinerated together with the studied product. That gives rise to an allocation problem because it is impossible to say exactly which product that contributes to the environmental impacts and to what extent. The total environmental impact therefore needs to be split between them. This can be solved by different approaches, namely by increasing the level of detail in the assessment, using partitioning or system expansion (Baumann et al., 2004). This will, however, not be described in further detail in this master thesis.

After the system boundaries have been determined, the emissions occurring in the life cycle should be investigated in order to determine which impact categories that should be included. These categories include different emissions that can give rise to environmental- and human impacts. Some examples of impact categories are *climate change*, *human toxicity*, *acidification* and *eutrophication* (Baumann et al., 2004).

Within the goal and scope definition it is also important to describe which type of LCA that should be used, either an *attributional* or a *consequential* (Baumann et al., 2004). The first one is about assessing physical flows connected to the life cycle of a product or a system, which might affect the environment in a positive or negative way. The second type, the consequential LCA, is about assessing how these flows changes as a certain decision is made and thus how the environmental impacts from a product or a system are connected to that decision (Ekvall et al., 2016).

These two types of LCAs can be referred to by other names, such as *descriptive* and *change-oriented* respectively, but nevertheless are the two types focusing on different situations, as already mentioned. As a result of that, the two types uses different kinds of data where the attributional LCA generally uses average data whereas the consequential LCA uses marginal data (Finnveden et al., 2009). Additionally, there is a difference in how much data that is included in the assessment. For example, in attributional LCAs it is common to include as much as possible, even the production of capital goods. For consequential LCAs on the other hand, the choice on what to include or not depends on which parts of the life cycle that are actually affected by the decision. Only the parts that changes due to the decision are thus included in such assessments (Baumann et al., 2004).

Lastly, a description on how the data will be collected, which assumptions that are made and how the result will be presented should be included in the scope definition (Baumann et al., 2004).

Inventory analysis
The second step in the framework of an LCA is the life cycle inventory (LCI) analysis. This step can basically be divided into three main activities: construction of a flow model, data collection and calculations. An extensive flowchart should be presented, which should include all the processes that will be investigated in the study based on the system boundaries. Data is thereafter collected for all processes from different sources, such as databases. At the same time, material- and energy balances are performed. Both the collected data and the results from the calculations are normalized into the functional unit that was determined in the goal and scope definition (Baumann et al., 2004).

Impact assessment
The third step in the LCA procedure is to perform a life cycle impact assessment (LCIA). This step is divided into two mandatory steps, namely *classification* and *characterization*, as well as other voluntary steps (Baumann et al., 2004).

Classification is about grouping the emissions calculated in the LCI step into relevant impact categories determined in the goal and scope definition. A specific emission can be grouped into several impact categories since it might have the potential to contribute to more than one type of environmental impact. A schematic illustration is often constructed with the purpose of visualizing all the emissions that are released in the whole life cycle and which potential environmental impacts they can give rise to (Baumann et al., 2004).

After the emissions have been classified into impact categories, a characterization is necessary. Each emission has a specific equivalence factor in each impact category that is multiplied with the results from the calculations in the LCI. One single unit is obtained for each of the impact categories which makes it possible to visualize the results in, for example, diagrams. This makes the comparison between different products more concrete, which in turn makes it easier to identify the product that causes the largest environmental impact (Baumann et al., 2004).

The classification and characterization are mandatory according to the ISO standard 14040. However, it is possible to include other voluntary steps as well, such as *normalization* and *weighting*. The aim of the first mentioned is to translate the result from the impact assessment into results that can be easier to grasp. A reference unit is therefore used when performing this translation. The latter step means that the result from the impact assessment is weighted into one single score for the environmental impact, based on subjective judgments (Baumann et al., 2004).

When large studies are performed, there are often a lot of data that needs to be handled, which can make the LCIA time consuming. For such studies it exists LCIA methods that are ready-made for the user. Such methods includes all LCIA steps (classification, characterization etc.), which is beneficial for the user since there is no need to perform this part of the assessment by hand. Instead, a software performs it and delivers a characterization indicator or an index (Baumann et al., 2004).

Several LCIA methods exists to choose from, all of which have their own approach to the LCIA (Baumann et al., 2004). Examples of such LCIA methods are CML, Eco-Indicator, EDOP, ReCiPe and USEtox. The first mentioned is the most commonly used method because it limits uncertainties of the assessments since it excludes a quantitative modelling of late stages in the cause-effect chain that most often are more uncertain. The results from the inventory analysis are grouped into different midpoint categories, for example climate change (Ruggles et al., 2017; GaBi, 2017a). Another method, the Eco-Indicator, also follows the procedure where the inventory results are grouped into midpoint categories. This method does, however, take it one step further by weighting the data according to a social evaluation process and it is thus often used for comparing different types of environmental impacts. The results from this method are presented as a single number: an Eco-Indicator score (Ruggles et al., 2017). The choice of impact assessment method therefore affects the results of the LCA and should thus be made carefully.

Interpretation
Finally, the results from the LCA are interpreted and some parts might be necessary to adjust. In addition to this, the robustness of the result can be tested using sensitivity analysis, uncertainty analysis and variation analysis. Another way of checking the results is to perform a critical review of the report. Such a review is mandatory if the aim is to publish the report (Baumann et al., 2004). These last steps will not be described further in this master thesis.

2.3.2 Software for LCA

In an LCA there are a lot of calculations necessary, which can be very time consuming to perform by hand. Being able to perform the calculations with a software both shortens the time spent on the calculations and opens up the possibility to make changes in sensitive and/or uncertain parameters (GaBi, 2017b). The output from an LCA software can be detailed information about the environmental impact for each process in the assessed model, but also presentations of the differences in environmental impact for different types of scenarios. The results can therefore be used for different purposes, such as identifying main contributors to a certain impact category. The exact type of output from a software thus depends on how it is used (GreenDelta, 2017).

There are a lot of different types of software on the market that can be used. Most of them are expensive, but the one used in this master thesis, openLCA, is free of charge and was developed by GreenDelta (GreenDelta, 2017). One reason for choosing this software is that it can be used without license and is thus possible to be shared with others. This is also one of the reasons for using openLCA in consultancy applications. Other areas where this software can be used are in the industry and for research. All these actors can use the software for different purposes, such as LCA, Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA), Carbon and Water footprints and Environmental Product Declarations (EPD) (Winter et al., 2015; GreenDelta, 2017).

In order to perform any LCA calculations with openLCA, one or several databases have to be imported to the software. The purpose of importing a database in openLCA is to make sure that the software has data that can be used for the calculations. These databases are sets of data available online and includes data that fits a lot of different application areas (GreenDelta, 2017). Such databases can be free of charge, but the one used in this master thesis, Ecoinvent, had to be purchased. This database contains large amounts of data over thousands of products, such as the amount of emissions released to the environment caused by for example the production of 1 MJ electricity or 1 kg of steel (Ecoinvent, 2017a).

Within Ecoinvent there are three different types of system models to choose between, namely the Cut-off system model, the Allocation at the Point Of Substitution (APOS) system model and the Consequential system model. The first two models are variants of the attributional LCA, which were described in Section 2.3.1. The main difference between these two system models is that they allocates the waste treatment products and recyclable materials in different ways.

In the cut-off system model, this is allocated in such a way that the primary producer[1] is responsible for the production of their product while the secondary producer[2] is only responsible for their production. As a consequence of this, the primary producer will not obtain any credit for choosing recyclables while the secondary producer is not responsible for any impacts occurring upstreams in the value chain. On the other hand, the APOS system model allocates the burden to specific processes. Consequently, it means that all possible by-products produced in different treatment processes are allocated to the specific process that produces the product in the first hand. Lastly, the consequential system model is used for assessing the changes in the environmental impact caused by a certain decision (Wernet et al., 2015; Ecoinvent, 2017b).

3. Method

This master thesis was divided into three parts, all of which corresponds to one of the three objectives presented in Section 1.3. The initial screening is connected to the first objective whereas the detailed assessment and the literature review of sustainable digitalization are connected to the second and third objective respectively. This section of the report is therefore divided into these three parts where different methods are presented.

The main method used throughout the project was LCA, but it was mainly used in the initial screening and it is thus described more thoroughly in that section. Literature studies was another important method used throughout the master thesis, mainly in relation to the second and third objectives and is thus described to a larger extent in those sections.

3.1 Initial screening

The method (LCA) used in the initial screening is described in this part of the assessment, which is connected to the first objective, defined as:

"Which are the five critical areas in the factory based on the following factors: emissions of greenhouse gases (GHGs), depletion of abiotic resources and emissions of other compounds that can give rise to eutrophication, acidification, human- and environmental toxicity, photochemical oxidation and ozone layer depletion?"

The methodological choices performed in the LCA are presented together with the different assumptions made. The approach used in openLCA is thereafter explained, followed by a description on how the critical areas were chosen.

3.1.1 Goal and scope definition

This section describes which methodological choices that were made in the LCA.

The type of LCA that was considered appropriate in this assessment was an attributional LCA. An unwritten rule is to choose an attributional LCA rather than a consequential LCA. A justification for this rule is partly that it is a more widely spread method but also because it is quite pointless to use the consequential LCA if there are no decisions to be made (Finnveden et al., 2009). In this master thesis, the aim was not to assess changes in the environmental impact

[1] Producer of the first product
[2] Producer of the second product

caused by a certain decision but rather to assess relevant physical flows in the environment and thus was an attributional LCA chosen.

OpenLCA was used as a software for the whole master thesis since it can be used without a license and is thus possible to be shared with others, such as those involved in Smart Factories at Universeum. Additionally, Ecoinvent was used as a database because it contains large amount of data and is widely used among experienced LCA users.

The type of system model that was chosen in this study was the APOS system model. The two different types of system models that are appropriate to use when conducting an attributional LCA are APOS and Cut-off. Since the only difference between these two models is the allocation of waste treatment products and recyclables materials, a consideration was made regarding the materials used and waste produced within the factory. The main material in the VR glasses is corrugated paper, which produces relatively much waste during its production and the assemblage. The waste is sent to recycling facilities where it is sorted and recycled. This is important for the overall environmental impact of the factory and should be taken into account when it is assessed. For that reason, the APOS system model was chosen.

CML was considered as an appropriate impact assessment method. The main reason for choosing this method was that it limits the uncertainties since it only consider the early stages in the cause-effect chain. That was important for this project since there already were a lot of uncertainties regarding, for example, the weight of the engines in the rotation press.

The functional unit chosen was "X number of VR glasses produced per year". The "X" refer to 300 000 and 30 000 respectively, which are estimations on the annual production in the factory during its first two years at Universeum and the following years at Lindholmen. The reason for choosing two variants of the functional units was that there are quite large differences in the amount of produced VR glasses depending on where the factory is located, which in turn might affect the critical areas.

In CML there are 11 different impact categories, which are presented in Table 1. During the initial screening, all of these categories were considered as important and thus analyzed to an equal extent. Throughout the report, changes in the environmental impact of the factory are described and all of those refer to changes in these 11 categories. There are thus no distinctions made between emissions to the environment and resource consumption.

Table 1. *Impact categories used in the initial screening.*

Impact category	Unit
Climate change	kg CO_2-eq
Acidification	kg SO_2-eq
Eutrophication	kg PO_4^{-3}-eq
Depletion of abiotic resources - fossil fuels	MJ
Depletion of abiotic resources, elements - ultimate reserves	kg antimony-eq
Freshwater aquatic ecotoxicity	kg 1,4-dichlorobenzene-eq
Marine aquatic ecotoxicity	kg 1,4-dichlorobenzene-eq
Terrestrial ecotoxicity	kg 1,4-dichlorobenzene-eq
Human toxicity	kg 1,4-dichlorobenzene-eq
Ozone layer depletion	kg CFC-11-eq
Photochemical oxidation	kg ethylene-eq

A cradle-to-gate approach was considered appropriate for the purpose of this LCA. This means that everything that happens to the VR glasses after the visitors have obtained them (use-phase and end of life treatment) were excluded from the study. The reasons for excluding these parts are that there is a large number of uncertainties regarding what will happen to the product during the use phase and how the waste handling is performed.

The geographical boundary chosen for this LCA was Europe because there was a lack of data for Sweden specifically in Ecoinvent. For some processes, however, Swedish data were available and therefore used. An example of such data is the electricity where the Swedish average electricity was available and thus used.

Two upstream processes per process in the life cycle of the VR glasses were chosen to be included in the LCA. This decision is motivated by the recommendation to include as much as possible when performing an attributional LCA, as mentioned in Section 2.3.1. In practice this means for instance that the construction of capital goods, such as trucks, were included in the assessment. This choice was further motivated by performing a quick check on how much the result changed as the number of upstream processes included in the assessment changed from one to two. The result from this was that for all processes in the life cycle, there was at least one impact category that had an increase larger than approximately 50 %, which means that it is appropriate to include more than just one upstream process for all parts in the life cycle of the VR glasses.

It was decided not to set any specific boundary for the temporal boundary since that was not relevant for the study. The reason is that the use phase is excluded from the study and therefore is the life length of the product not relevant. Additionally, the factory will not be used to such an extent that any of its components (e.g. robots) needs to be replaced before the factory is dismantled.

Finally, the assumptions made throughout the initial screening are listed, and motivated, below.

- The components used in the factory, such as the transport systems, are assumed to be produced specifically for this factory and will not be used for any other purposes after the factory has been dismantled. This assumption is motivated by the fact that an allocation problem can be avoided. The environmental impact caused by these components in this study will thus be higher than if an allocation had been performed.

- The waste that are produced during the production of the materials, used in the components within the factory, are excluded from the study since it was considered to be too time consuming to identify such data.

- The corrugated paper sheets were assumed to consist of 100 % virgin material. Stora Enso use some amount of recycled fibres in the production of corrugated paper but this amount was unknown. A worst case scenario with only virgin material was therefore used for the calculations.

- The racks were assumed to be produced with thermoforming. This is because the racks will most likely be produced with vacuum forming, according to Christian Forsström[3]

[3] Personal contact: Christian Forsström (Fristad Plast)

at Fristad Plast, and thermoforming was the only vacuum forming process available in Ecoinvent and was therefore chosen.

- The total amount of racks produced was assumed to be 300. This was decided based on the number of racks per transport from Fristad Plast to Universeum, which are 100. It was also assumed that the same amount of racks should be present at Universeum and for refilling at Fristad Plast simultaneously.

- The height of the racks was assumed to be 200 mm based on the information about the other dimensions and the size of the lenses.

- It was assumed that the transport of racks from Ösönerplast would not contribute significantly to the environmental impact and this transport was therefore excluded from the calculations. The reason for this is that the distance between Ösönerplast and Fristad Plast is less than 20 km and this transport will only be needed once.

- The ordering station was assumed to consist of six displays. The reason for doing this assumption was that the layout of the ordering station was not decided upon as the calculations had to be made. Consequently, an assumption was required. Six displays were considered as appropriate since that was a suggestion under discussion by the project managers in the beginning of the project.

- The weight of the cameras for QR testing was assumed to be the same as the vision cameras (required for the positioning of the robots), namely 0.736 kg.

- One component in the first production line is the input to the press, Figure 3, and its weight was assumed to be 30 kg. This assumption was based on comparisons with other components in the factory and the given dimensions of this component.

- The weight of the two engines that drives the rotation press was assumed to be 10 kg each. This assumption was based on comparisons with the weight of the other engines in the factory.

- The ENP transport system was assumed to have a total weight of 30 kg and the engine was assumed to have a weight of 5 kg. This assumption was based on comparisons with other components in the factory and the given dimensions on this transport system.

- One component in the first production line is the output from the press, Figure 3, and its weight was assumed to be 15 kg. This assumption was based on comparisons with other components in the factory and the given dimensions of this component.

- The Flexlink transport system was assumed to have a total weight of 110 kg where the aluminum parts weighs 90 kg and the engine and plastic parts weighs 10 kg each. All plastic parts in the transport system were assumed to be made out of polyethylene (PE) even though it contains polyoxymethylene (POM) as well. The latter plastic was, however, not available in Ecoinvent and all plastic parts were thus assumed to be made out of PE.

- The weight of the different components included in the Eton Systems transporter was assumed to be 160 kg steel, 75 kg aluminum, 10 kg polycarbonate (PC) and 5 kg for the engine. This assumption was based on comparisons with other components in the factory and the given total weight of this transport system.

- The assemble station was assumed to consist of two tables with a wood sheet and four steel legs respectively. The dimensions of the tables were assumed and thus could a volume of the wood sheet and the weight of the steel legs be calculated. It was also assumed that the assemble station would consist of two displays where the visitor receives information about how to put together the VR glasses.

- The factory will be recorded by cameras, and the number of cameras were assumed to be the same as the number of production lines, namely two.

- All the electricity, both for the production of the components in the factory but also the amount needed to run the factory, was assumed to be Swedish average electricity. This assumption was made because the location of the production of the different components in the factory was not known and therefore was Swedish average electricity considered to be a better assumption compared to, for example, a global average electricity. In addition to this, the factory will only be located in Sweden which means that the electricity used to run the factory is mainly Swedish average.

- The actual assembling of the different components (e.g. the robots) was excluded from the study since it was considered to be too time consuming to get such detailed information from the suppliers. This means that from this point, when referring to the production of a certain component it includes the production of the raw material and not the assembling of the components. One exception is, however, for the plastic components that includes injection moulding or thermoforming, which is a part of the actual production process.

- The transports of the components (except for the lenses, racks and corrugated paper sheets) from their production sites were excluded in this study. The reason for this assumption is that this type of transport is a onetime occasion that is considered as negligible.

- The factory was assumed to be run at full speed for five hours per day. This assumption was made because it was hard to estimate how many visitors that actually will run the factory and how many of those that will run the factory simultaneously, which affects the running time. Therefore, this estimation was instead based on the opening hours of Universeum.

- It was assumed that maintenance of the factory is needed 12 times per year because it was considered to be too time consuming to identify a more realistic scenario for the maintenance. This assumption therefore represents a worst case scenario.

3.1.2 Inventory analysis

The inventory analysis was partly about collecting data and partly about calculating the emissions and resource consumption in relation to the chosen functional unit, as mentioned in Section 2.3.1. The inputs and outputs required in the production of VR glasses are presented in Table 2.

Table 2. *An overview over the inputs and outputs required to produce VR glasses in the factory*.

Input	Output
Corrugated paper sheets	VR glasses
Lenses	Waste
Racks	
Transports	
Electricity	
Storage	
Sensors	
Cables	
IRB 1200 robot	
Re-fixture	
Labelling station	
QR testing	
Input to press	
Rotation press	
ENP transporter	
Output from press	
Flexlink transporter	
Scara robot	
Eton Systems transporter	
Output of lenses	
Assemble station	
Safety cage	
Ordering station	
Cameras	
Other (e.g. actuators and screws)	

Each of the inputs in the table above can be described in a more detailed level with their own inputs. For example, the IRB 1200 robot requires a certain amount of steel and aluminum during its production. Data for some of these inputs were collected from the suppliers of the products, where Stora Enso for example provided information about the amount of corrugated paper sheets needed to produce a pair of VR glasses. All of this data are presented in Appendix I.

Some of the data from the suppliers had to be processed in different calculations in order to fit the format of the software and these calculations are presented in Appendix II. An example of such a calculation is when the weight of the racks was calculated based on its measurements, which were partly provided by Johan Bengtsson[4] and partly an assumption made the authors of this report. The reason for calculating the weight of the racks is that the software requires a specific weight and not the measures.

The suppliers did not have any information about the specific emissions related to the production of the components though. That data were therefore taken from Ecoinvent instead (Wernet et al., 2016).

After all of the data were added into openLCA, a product system could be created in which a model graph was obtained, Figure 7. Based on the product system, the calculations could be

[4] Personal contact: Johan Bengtsson (GTC)

performed within the software. In openLCA, the LCI is combined with the LCIA in the sense that the software calculates the emissions and resource consumption in relation to the functional unit at the same time as it performs the classification and characterization. In other words, the results from the LCI are used for LCIA calculations in openLCA, but it is performed in one step. This means that the results from the calculations in the inventory analysis are not directly visualized for the user of the software. On the other hand, the results from the impact assessment are of bigger relevance, which is described in the next section.

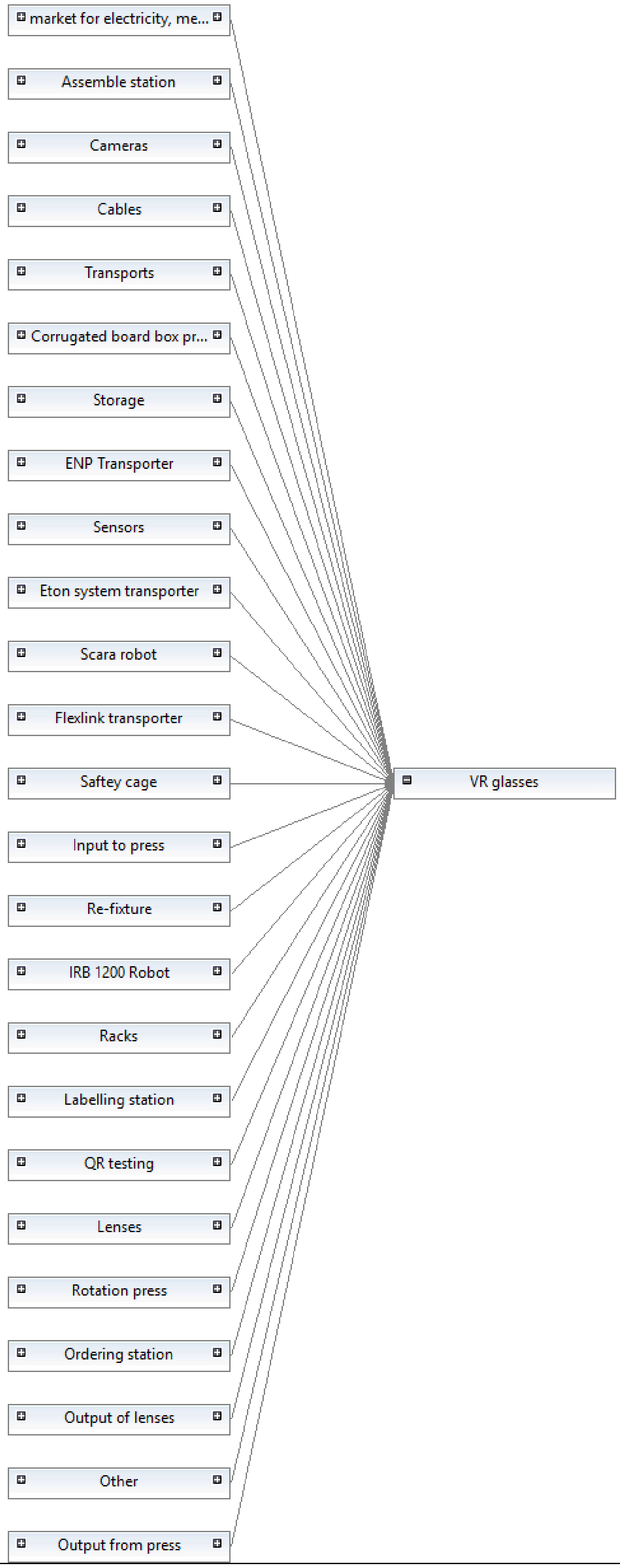

Figure 7. *The model graph created by openLCA based on the inputs in Table 2.*

3.1.3 Impact assessment and Interpretation

The impact assessment was about classifying the different emissions over the whole life cycle into different impact categories and thereafter perform a characterization where equivalence factors for each impact category are multiplied with the result from the inventory analysis, as described in Section 2.3.1.

The results from the LCI are used in the calculations in the LCIA and the results from those calculations are presented in several ways in openLCA, such as lists, Sankey diagrams and pie diagrams. The results were extracted and used to construct a bar chart for each impact category. The purpose of this was to be able to compare the impacts related to the different processes in the life cycle and thus facilitate the selection of the critical areas. The approach used to select the critical areas is described below.

The processes that contributed with more than 2 % of the total impact in each impact category were listed, both for the production of 30 000 and 300 000 VR glasses. Thereafter, the five processes that occurred most frequently in these lists were selected as the critical areas. These areas were in focus in the detailed assessment.

3.2 Detailed assessment

During the second part of the project, the detailed assessment, the five critical areas identified in the initial screening were assessed in more detail. This part of the assessment is connected to the second objective, defined as:

"Would it be possible to reduce the environmental impact and resource consumption of the critical areas? How can these improvements be performed and to what extent do those improvements reduce the total environmental impact of the factory?"

Five approaches were used to answer these questions. Those approaches are further described in the sections below.

3.2.1 Alternative processes and raw materials

The first part of the detailed assessment was to identify why each critical area contributed to the different impact categories. In other words, which production processes (within each critical area) that gives rise to the largest emissions in the different impact categories were identified. An example of such a process can be the production of linerboard, if the production of corrugated paper sheets is identified as a critical area.

This was done by creating a separate product system in openLCA for each critical area and thereafter run the calculations. The results from those calculations are, for example, a contribution tree that clearly states to what extent each process contributes to the total environmental impact in all impact categories.

In order to increase the knowledge and understanding about the identified processes within each critical area, literature studies were performed for each process. Additionally, literature studies on possible alternative processes were done to see if there is a possibility to choose other production processes that can reduce the overall environmental impact of the critical area and thus also of the whole factory. If such alternatives were identified, those were tested in openLCA (if available in Ecoinvent) to get a quantification of the possible reduction of the environmental impact. Additionally, similar calculations were performed for some of the identified improvements simultaneously in order to see how much the total environmental impact could decrease. From these results, new critical areas could be identified.

3.2.2 Alternative volumes

There are mainly two consumables in the factory, namely corrugated paper sheets and lenses. On request from the project managers of Smart Factories, the volumes of these two consumables were decided to be analyzed in order to investigate to what extent the environmental impact is affected by changes in the production volume. This was partly done in the initial screening where the calculations were performed for both 300 000 and 30 000 VR glasses.

In this part of the project, this was done in a more detailed manner with scenario analysis. The difference between the initial screening and this part of the project is that during the initial screening, the calculations were done for a pre-defined layout of the factory decided by the project managers. The analysis in the detailed assessment took it one step further by testing alternative layouts and consumption volumes of the factory.

The alternative layout tested in the scenario analysis was that there are 30 VR glasses next to the factory that the visitors can use. This can reduce the number of VR glasses produced each year because some visitors arrives to the factory in larger groups, such as school classes. If all of those visitors were to run the factory it would be quite time consuming. Instead, this change makes it possible for the group to run the factory a couple of times to see its function and the rest of the group can try the existing VR glasses next to the factory.

The visitors that still choose to run the factory will have the opportunity to leave their VR glasses at Universeum if they do not want to bring them home. An environmental benefit of this is that the glasses have the possibility to be reused several times at Universeum, which is an important aspect in a sustainable society. This will keep the number of test glasses at a constant level of approximately 30 VR glasses.

A prerequisite for the reuse to work is that there are no names written on the glasses, which means that the labelling station should only print the QR codes on the product and thus not any additional texts. As a consequence, the amount of ink used in the factory will be reduced.

There are two QR codes on the glasses, one of which is used to start the lens line and the other to ensure a correct waste handling by the visitor at the assemble station, as mentioned in Section 2.1. For those glasses that are ready-built next to the factory, there will be a sticker on the QR code in order to reduce the risk of confusion for the user.

Three different scenarios were tested in this part of the project and those are listed below.

- Scenario 1: 75 % of 300 000 visitors wants to run the factory per year
- Scenario 2: 50 % of 300 000 visitors wants to run the factory per year
- Scenario 3: 25 % of 300 000 visitors wants to run the factory per year

The results for each scenario were compared to the reference scenario in order to see how much the environmental impact decreases for each impact category. The reference scenario is the case where the factory produces 300 000 VR glasses and the layout of the factory is as the one described in Section 2.1.

The parameters that were affected by a change in volume and thus also changed in openLCA were:

- The electricity consumption
- The consumption of corrugated paper sheets
- The consumption of lenses
- The consumption of ink
- The amount of transports (excluding the maintenance, which were assumed to be the same as in the reference scenario)

3.2.3 Alternative dimensions

The third part of the detailed assessment was to analyze how the environmental impact changes as other dimensions are used for the lenses, racks and corrugated paper sheets. How this part was performed is explained in more detail below. The calculations performed by hand in this part of the assessment can be seen in Appendix II.

Lenses
The two lenses are currently connected between the eyes and can thus be seen as one item with a total weight of 10 g, Figure 2. The lenses have a diameter of 25 mm each and the connection between them is approximately 20*5 mm. The reason for choosing this type of lenses was that it was considered to be more technically feasible to transport the lenses in the factory if the Scara robot and Eton Systems transporter had a piece to hold on to. This is the reference scenario.

If the lenses were to be separated, its diameter had to be at least 34 mm due to health risks for the young visitors at Universeum. Since the decision was made to have the lenses connected, their diameter could be reduced to 25 mm though.

This part of the detailed assessment looked at how the environmental impact is affected by this type of restriction. For example, if the factory was not located where there are children, the diameter could be 25 mm even though the lenses were not connected between the eyes. That would reduce the total weight of the lenses and thus the use of polymethyl methacrylate (PMMA), which is the plastic used in the lenses.

The dimensions assessed in this part of the detailed assessment were:

- Scenario 1: Two separate lenses with a diameter of 25 mm (9 g), stored in a corrugated board box with the dimensions of 60*30*10 mm (1.4 g)
- Scenario 2: Two separate lenses with a diameter of 34 mm (17 g), stored in a corrugated board box with the dimensions of 60*30*10 mm (1.4 g)

How much the environmental impact changes for the two different scenarios were calculated in openLCA in the same way as in the initial screening. The parameters that were affected by a change in the dimensions of the lenses and thus also changed in openLCA were:

- Consumption of PMMA
- Consumption of corrugated paper
- The cargo of the transports from Stora Enso and Fristad Plast to Universeum respectively

Racks
The dimensions of the racks used in the initial screening were 300*400*200 mm with a thickness of 2 mm, which equals a weight of 1 kg. The depth and length (300*400 mm) of the racks were chosen by the project managers of Smart Factories in such a way that eight racks could fit on the ground floor of an EU-pallet. The height (200 mm) was, on the other hand, an assumption made in the initial screening.

The dimensions assessed in this part of the detailed assessment were:

- Scenario 1: 600*400*200 mm (which makes it possible to have four racks on the ground floor of an EU-pallet) with a thickness of 2 mm that equals to a weight of 1.8 kg.
- Scenario 2: 600*800*200 mm (which makes it possible to have two racks on the ground floor of an EU-pallet) with a thickness of 2 mm that equals to a weight of 2.5 kg.
- Scenario 3: 300*400*200 mm (which makes it possible to have eight racks on the ground floor of an EU-pallet) with a thickness of 1 mm that equals to a weight of 0.5 kg.

The parameters that were affected by a change in the dimensions of the racks and thus also changed in openLCA were:

- Consumption of polystyrene (PS)
- Number of racks
- The cargo of the transports between Fristad Plast and Universeum

Corrugated paper sheets
The dimensions of the corrugated paper sheets used in the initial screening are 600*400 mm. In the beginning of the project there were discussions among the project managers if the measures could be decreased to 600*350 mm. However, that would not result in any technical benefits at Stora Enso or increase the number of sheets per pallet. This proposal was therefore not chosen. Although, these measures were tested in openLCA in this part of the detailed assessment in order to see how much the environmental impact could have been reduced.

Due to the new dimensions of each sheet, the total weight of the corrugated paper sheets were reduced from 27 000 kg to 23 625 kg for the case with 300 000 VR glasses. The reduction in environmental impact was calculated in openLCA in the same way as the total environmental impact was calculated in the initial screening. The parameters that were affected by a change in the dimensions of a corrugated paper sheet and thus also changed in openLCA were:

- Consumption of corrugated paper
- The cargo of the transport between Stora Enso and Universeum
- The number of the transports between Stora Enso and IL recycling and from Universeum to Hans Andersson recycling

3.2.4 Alternative layouts of the lens line

Looking at the lens line, there are several ways of adjusting it so that the number of components and/or their dimensions are reduced. Reducing the number of components or their dimensions were thought to reduce the environmental impact. To what extent that was true was calculated in openLCA in the same way as in the initial screening.

The three alternative layouts assessed in this part of the detailed assessment were:

- Scenario 1: The transport of the lenses from the Scara robot to the output of lenses is currently performed by an Eton Systems transporter with a weight of 250 kg. This scenario looked into a system with smaller dimensions of the transport system so that its weight was reduced to 180 kg, which was reasonable according to Tomas Nordlund[5] at Eton Systems.

- Scenario 2: This scenario was looking into a situation where the Scara robot and the Eton Systems transporter were replaced by an IRB 1410 robot, provided by ABB. The IRB 1410 robot has higher reach than the robots used in both the first and second production line. That was considered important since the distance from the racks to the output of lenses requires a larger reach of the robot. The weight of the IRB 1410 robot (225 kg) is thus higher than the robot used in the reference scenario (ABB, 2016).

- Scenario 3: Instead of having the lens line, this scenario looked at a situation where the lenses are stored in corrugated board boxes (100*30*10 mm, 3.2 g) within a vending machine. The visitor can obtain their lenses by scanning the QR code on the corrugated paper sheet.

The vending machine used in scenario 3 was assumed to be mainly made out of steel (50 kg), PC (6.5 kg), polyurethane insulation (PUR, 1.3 kg) and electronics (0.7 kg). These assumptions were made based on a vending machine with a height of 150 mm, width of 60 mm and depth of 1000 mm where the front is entirely made out of PC. The calculations of the weight for each material are shown in Appendix II.

The parameters that were affected by a change in the lens line and thus also changed in openLCA in some or all of the scenarios were:

- Consumption of material needed for Eton Systems transporter (in scenario 1, 2 and 3)
- Consumption of material needed for the IRB 1410 robot (in scenario 2)
- Consumption of material needed for the Flexlink transport system (in scenario 3)
- Consumption of material needed for the Scara robot (in scenario 2 and 3)
- Consumption of material needed for the output of lenses (in scenario 3)
- Consumption of material needed for the sensors (in scenario 3)
- Consumption of material needed for the cables (in scenario 3)
- Consumption of material needed for the safety cage (in scenario 3)
- The number of cameras used in the factory (in scenario 3)
- Consumption of corrugated paper (in scenario 3)
- Consumption of material included in the input called “Other” in Table 2 (in scenario 3)
- The cargo of the transports between Stora Enso to Universeum and IL recycling respectively and from Universeum to Hans Andersson (in scenario 3)

3.2.5 Alternative press

The last part in the detailed assessment was to look at another type of press. There exists several different types of presses and a flatbed-die cutter was chosen as an alternative in this part of the

[5] Personal contact: Tomas Nordlund (Eton Systems)

assessment. The reason for choosing this type of press was that there were a lot of discussions on whether to choose a flatbed-die cutter press or a rotation press in the beginning of the project.

How this decision affects the environmental impact was therefore considered interesting to look at. However, the rotation press used in the factory is a prototype of a real press and it is therefore hard to estimate how much another non-existing prototype press would weigh and what it would consist of. Although, the project managers gave a rough estimation of the material and weight of such a press, which was 0 kg aluminum and 20 kg more steel compared to the rotation press.

Calculations on how the environmental impact is affected by the choice of press were thereafter performed in openLCA in the same way as in the initial screening.

3.3 Sustainable digitalization in the literature

The last part of this master thesis was connected to the third objective, defined as:

"Identify to what extent the topic of sustainable digitalization is covered by scientific literature. Which topics do the authors of the scientific literature highlight as important and less important? Which topics require further studies?"

The reason for doing this literature review is that the topic of digitalization is relatively new and thus also the topic of sustainable digitalization. The aim of this part of the master thesis was therefore to initiate a literature review of the scientific literature covering this topic in order to identify which areas that requires further studies. This was mainly done in such a way that the identified reports were read and summarized.

Various databases were used for the literature review, but it was mainly google scholar and the website of Chalmers library that were used. Some search phrases used to find the reports were: "Digitalization and sustainable development", "ICT sustainability" and "Digitalization of industries".

To answer the questions in the objective, more detailed questions were formulated and those are listed below. These questions could be answered as the summaries were written.

- Does the authors of the reports refer to other, similar, studies?
- How does the distribution between governmental reports and scientific reports differ in Sweden?
- Which dimensions of sustainability are covered (i.e. economic, environmental or social)?
- Which topics are most frequently covered?
- Which topics are most common within each sustainability dimension?
- Does the authors of the reports suggest topics for further studies?

4. Results

The results are divided into three different sections, namely initial screening, detailed assessment and sustainable digitalization in the literature.

The results from the initial screening, Section 4.1, presents the five critical areas together with graphs of these for all impact categories. Some of these results are indirectly explained by the results from the detailed assessment and thus not explained in both places.

The results from the detailed assessment are presented in the same order as the five different approaches that were introduced in Section 3.2. Each approach investigates ways to reduce the environmental impact of the critical areas and its results are presented in Section 4.2 respectively.

Lastly, the results obtained in the final part of the project, sustainable digitalization in the literature, are presented in Section 4.3.

4.1 Initial screening

The results from the calculations performed in openLCA were used to construct bar charts for each impact category in order to visualize the contribution of each process. These charts are illustrated in Appendix III for 300 000 and 30 000 VR glasses, although the bar chart for the climate change is provided in Figure 8 as an example for the case with 300 000 VR glasses.

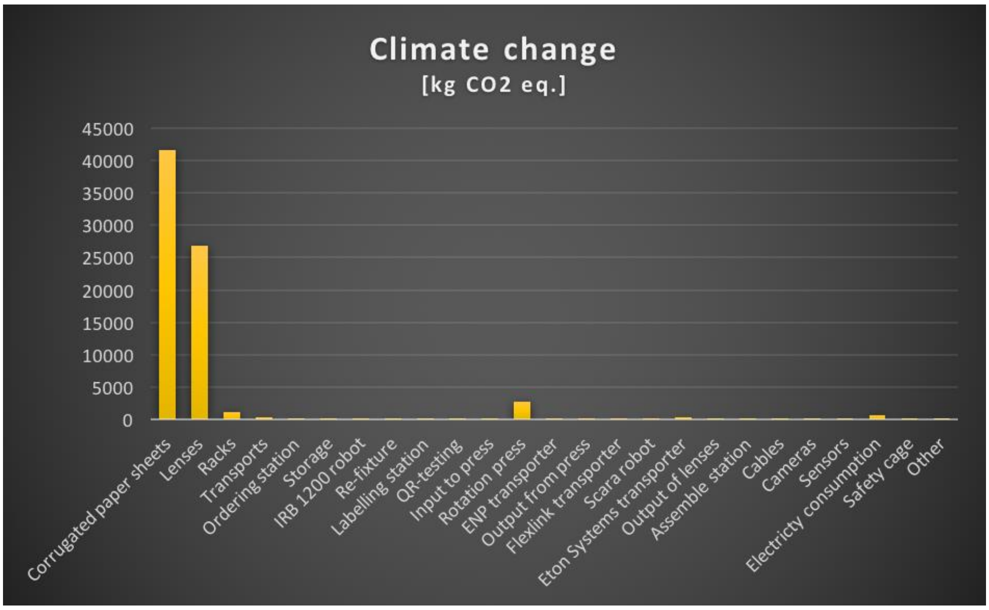

Figure 8. *An illustration of the contribution to the climate change for all parts of the life cycle for 300 000 VR glasses.*

Based on the results from the calculations, the five most frequently occurring processes, the critical areas, were identified through the 2 % limit approach. There is no change in the critical areas for the case with 300 000 VR glasses compared to 30 000 VR glasses. The critical areas are listed below.

- Production of corrugated paper sheets
- Production of lenses
- Production of racks
- Production of the rotation press
- Production of the Eton Systems transporter

In order to compare the environmental impact for these five critical areas, a bar chart for each impact category was constructed, Figure 9-19.

The number of produced VR glasses is a parameter that affects the importance of the different critical areas for each impact category, which can be seen in Figure 9-19. For instance, when 300 000 VR glasses are produced, it is mainly the production of corrugated paper sheets and lenses that contributes to the climate change, Figure 9. However, as the number of produced VR glasses is reduced to 30 000, the environmental impact of the other three critical areas becomes more significant. The reason for this is that the racks, press and Eton Systems transporter are not dependent on the volume of produced VR glasses.

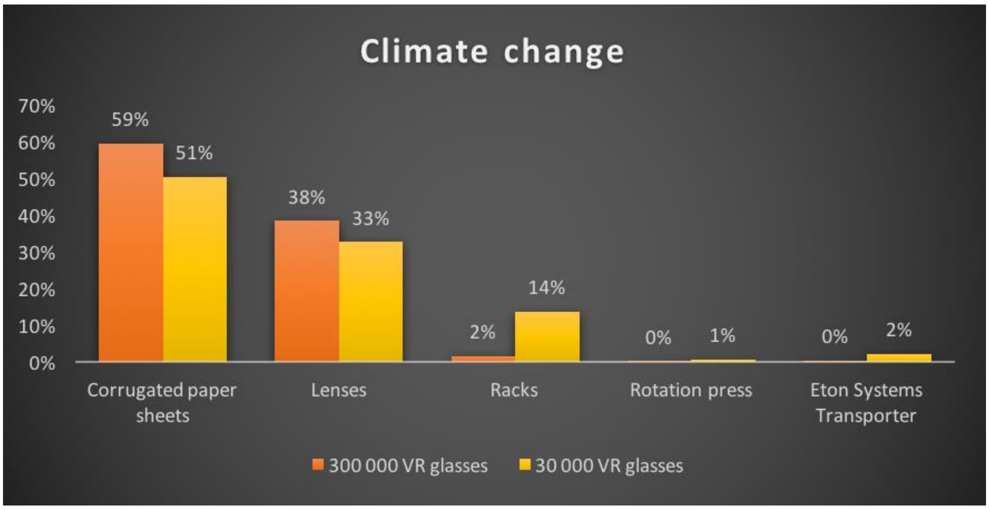

Figure 9. *An illustration of the climate change for 300 000 and 30 000 VR glasses for the five critical areas.*

The production of lenses contributes the most to acidification, no matter which of the two volumes of VR glasses that are assessed, Figure 10.

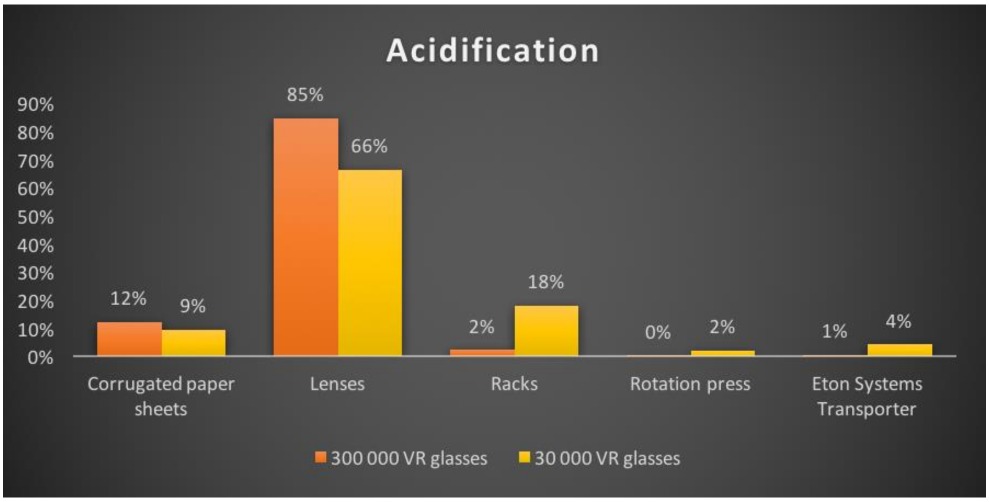

Figure 10. *An illustration of the acidification for 300 000 and 30 000 VR glasses for the five critical areas.*

In the case of eutrophication, the two critical areas that contributes the most in both cases are the production of corrugated paper sheets and lenses as illustrated in Figure 11.

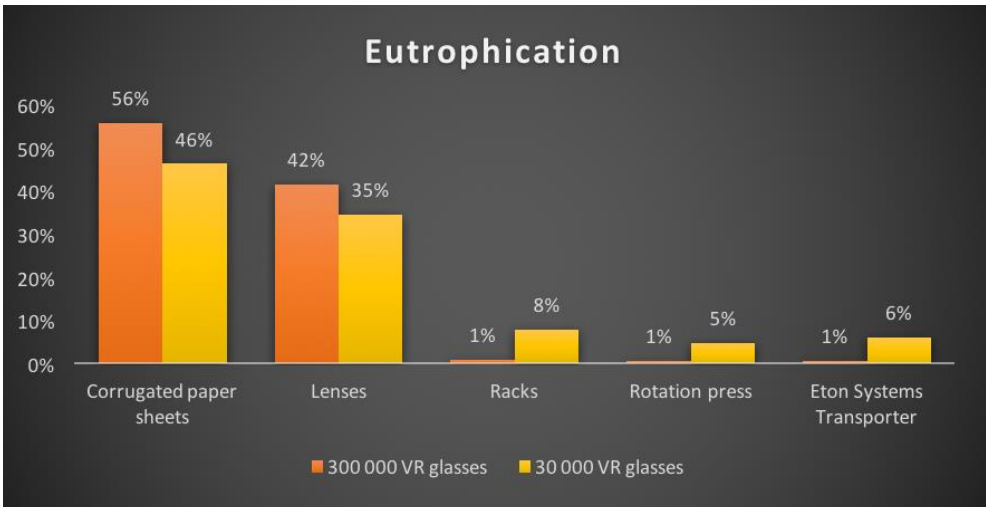

Figure 11. *An illustration of the eutrophication for 300 000 and 30 000 VR glasses for the five critical areas.*

The production of lenses contributes the most to the depletion of fossil resources but the production of the racks is also of importance, especially for the case with 30 000 VR glasses, Figure 12.

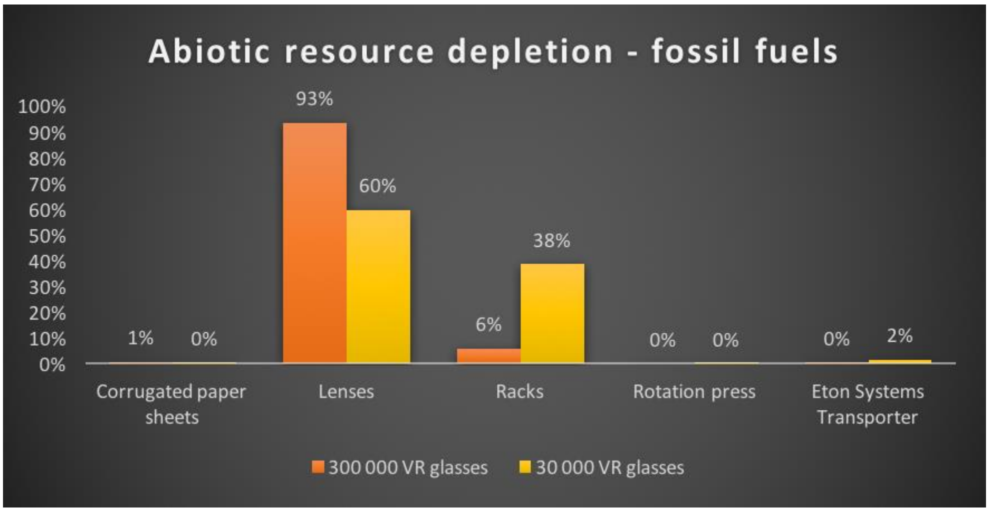

Figure 12. *An illustration of the abiotic resource depletion – fossil fuels for 300 000 and 30 000 VR glasses for the five critical areas.*

The patterns identified (i.e. increased significance of the areas that are not dependent on the volume of produced VR glasses as the volume decreases) in Figures 9-12 are similar for the depletion of ultimate reserves as well, Figure 13.

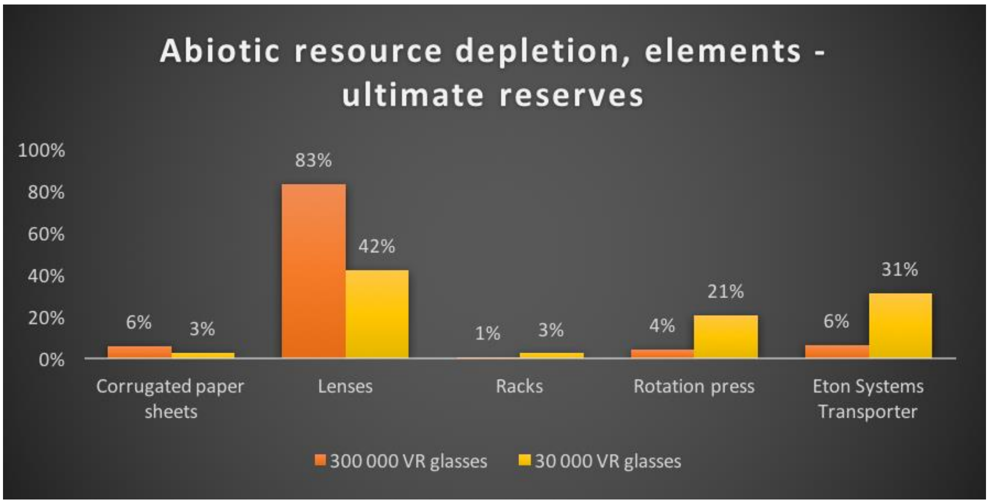

Figure 13. *An illustration of the abiotic resource depletion, elements – ultimate reserves for 300 000 and 30 000 VR glasses for the five critical areas.*

The production of lenses is responsible for the largest share of the freshwater ecotoxicity in both cases as Figure 14 illustrates. However, the share of the racks increases relatively much as the number of produced VR glasses changes from 300 000 to 30 000. Almost the same changes occur in the case of marine aquatic ecotoxicity as Figure 15 shows.

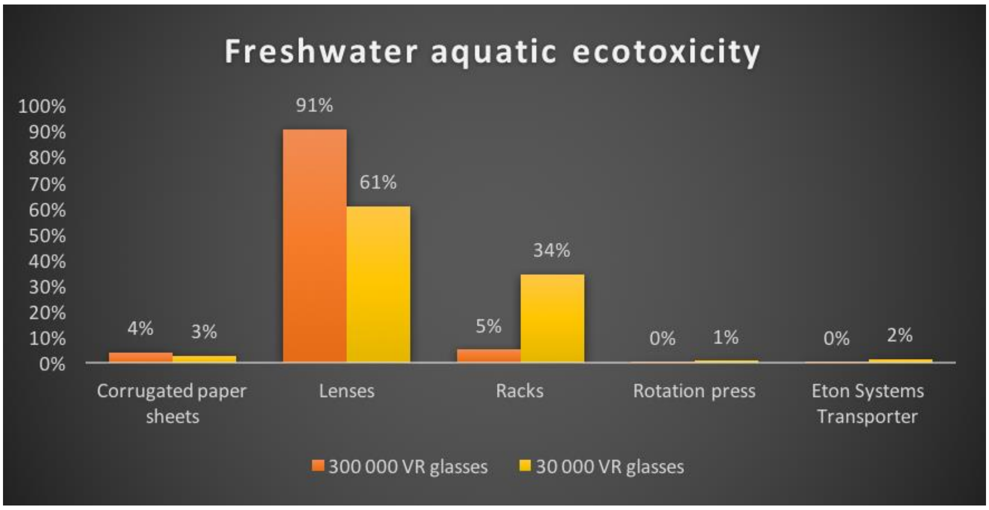

Figure 14. *An illustration of the freshwater ecotoxicity for 300 000 and 30 000 VR glasses for the five critical areas.*

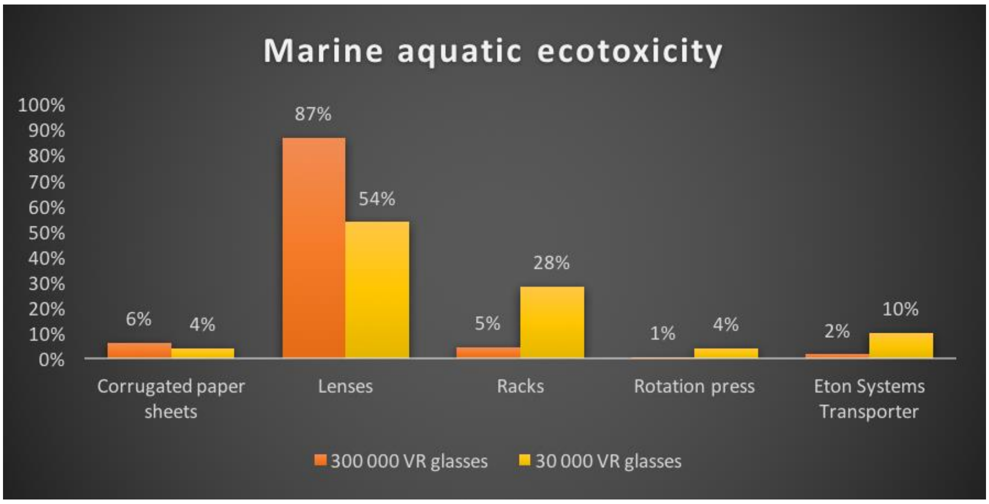

Figure 15. *An illustration of the marine ecotoxicity for 300 000 and 30 000 VR glasses for the five critical areas.*

All of the critical areas, except for the production of the racks, are of significance for the terrestrial ecotoxicity when the number of produced VR glasses are 300 000, Figure 16. The importance of the corrugated paper sheets and lenses are reduced in a way that they are relatively insignificant in comparison to the rotation press and Eton Systems transporter when the number of glasses are reduced to 30 000.

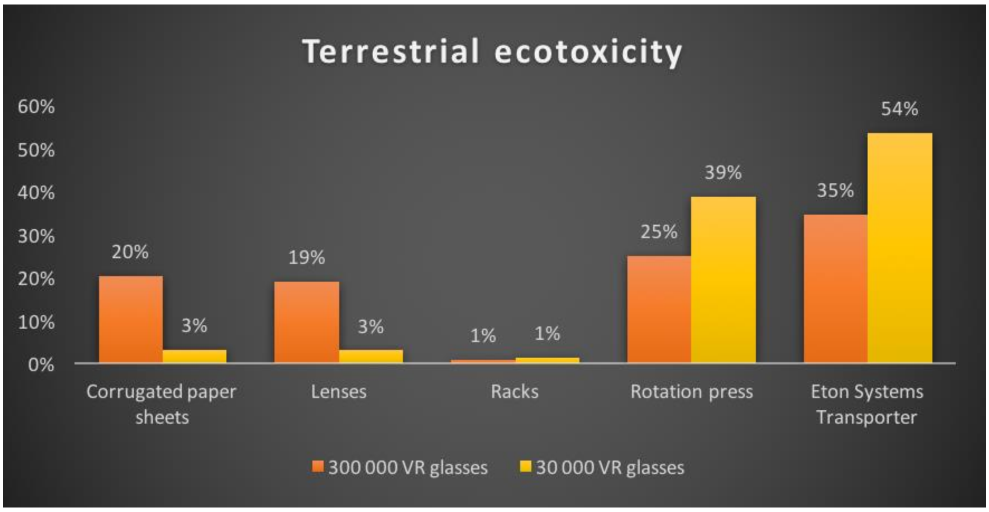

Figure 16. *An illustration of the terrestrial ecotoxicity for 300 000 and 30 000 VR glasses for the five critical areas.*

The Eton Systems transporter and the press contributes the most to the human toxicity, Figure 17.

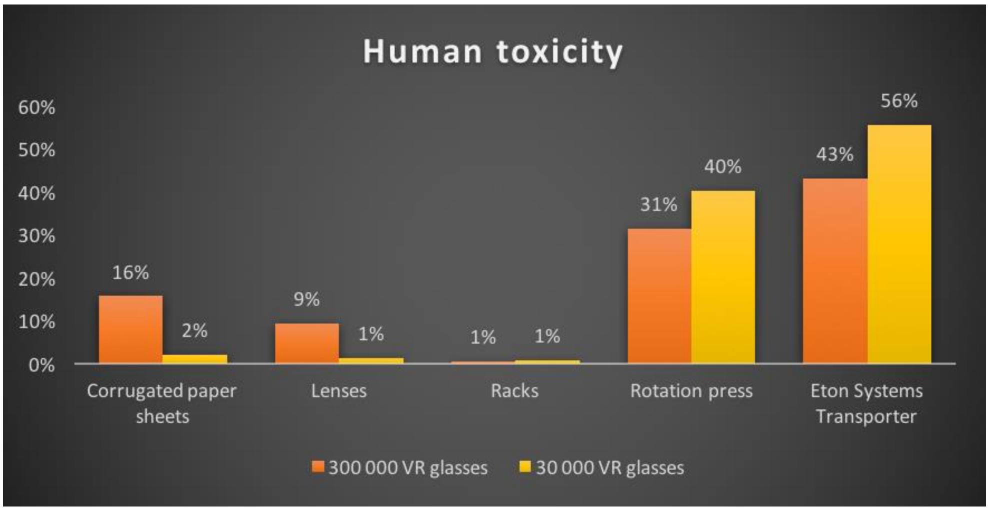

Figure 17. *An illustration of the human toxicity for 300 000 and 30 000 VR glasses for the five critical areas.*

The production of the corrugated paper sheets contributes the most to the depletion of the ozone layer in the case of 300 000 VR glasses as shown in Figure 18. On the other hand, in the case of 30 000 VR glasses, the importance of the rotation press is approximately the same as the corrugated paper sheets.

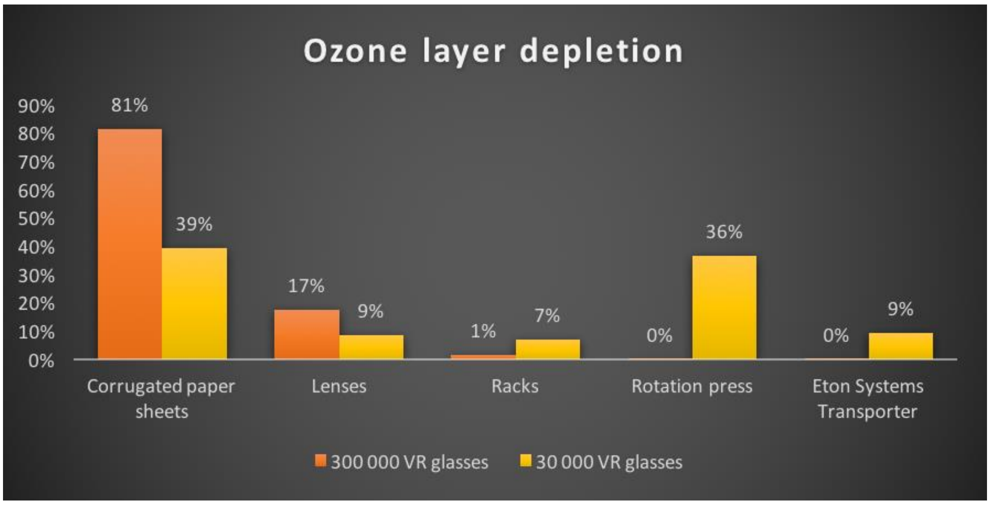

Figure 18. *An illustration of the ozone layer depletion for 300 000 and 30 000 VR glasses for the five critical areas.*

All of the critical areas are of significance for the photochemical oxidation in the case of 30 000 VR glasses, Figure 19. This is not the case with 300 000 VR glasses though since the production of lenses and corrugated paper sheets have a much higher share in that case.

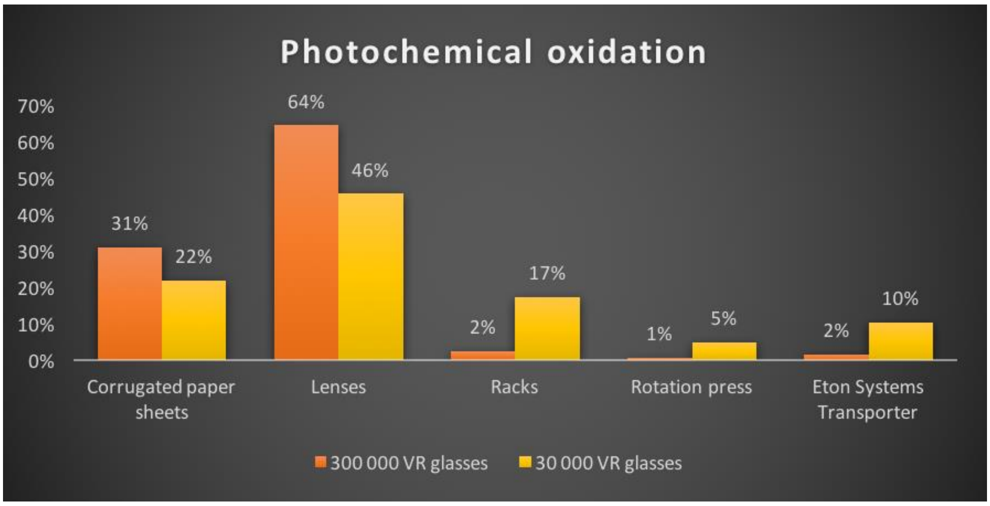

Figure 19. *An illustration of the photochemical oxidation for 300 000 and 30 000 VR glasses for the five critical areas.*

4.2 Detailed assessment

The detailed assessment was divided into five different parts and the results from each part are presented in the sub-chapters below.

In each of the sub-chapters, different calculations have been performed in order to decrease the environmental impact of the factory. The results are compared to the reference scenario which is the case with 300 000 VR glasses from the initial screening.

Throughout this section, there are some tables presenting environmental changes caused by a certain action aiming at decreasing the environmental impact caused by the critical areas. It is possible to identify which processes within the critical areas that lays behind these changes, but it will not be covered in this master thesis. The reason for this is that it lays beyond the time limit of this master thesis.

4.2.1 Alternative processes and raw materials

For each of the five critical areas (production of corrugated paper sheets, lenses, racks, rotation press and Eton Systems transporter), a literature study has been performed in order to increase the knowledge about the production processes that give rise to the largest environmental impact within each critical area. This was necessary in order to be able to suggest improvements for the processes, and thus also the factory. The results from this part of the project are presented below, starting with the corrugated paper sheets.

Corrugated paper sheets

In the production of the corrugated paper sheets, the processes that contributes the most to the environmental impact in all the impact categories are:

- Production of linerboard
- Production of fluting medium

Corrugated paper consists of a combination of linerboard and fluting medium. Linerboard is the flat paper whereas the fluting medium is the part between the two flat paper sheets (European Database for Corrugated Board Life Cycle Studies, 2017), which is visualized in Figure 20.

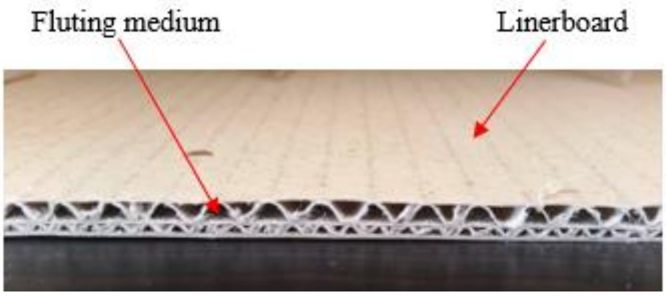

Figure 20. *The structure of a corrugated paper sheet.*

Linerboard can basically be divided into two different categories, namely kraftliner and testliner. The first mentioned is when the linerboard is produced from virgin fibres whereas the latter is linerboard produced from recycled fibres. The process that was used in the calculations in the initial screening was kraftliner. The fluting medium can also be made out of virgin or recycled fibres, where the first mentioned was used in the calculations in the initial screening as well (Exakta, 2017; Stora Enso, 2017). The reason for choosing virgin material in both cases was that during the initial screening it was not yet known if some of the material used at Stora Enso was produced from recycled materials. It was thus more appropriate to look at a worst case scenario with 100 % virgin materials.

Stora Enso has developed linerboard and fluting medium produced from 100 % recycled fibres. These are named “Avantliner Recyled” and “AvantFlute Recycled”, and are produced at Stora Enso´s mill located in Poland. Stora Enso in Skene imports some parts of these raw materials to produce their corrugated paper (Stora Enso, 2017). However, they also import virgin raw material from mills located in Sweden and Finland[6], which means that the finished product consists of a mixture of virgin and recycled materials.

The environmental impact caused by the production of corrugated paper sheets is affected by the choice of raw material. When recalculating the environmental impact (with 100 % recycled materials) from the initial screening (with 100 % virgin materials), it is clear that an increased share of recycled material is more environmentally friendly compared to the worst case scenario that was assumed in the initial screening, as can be seen in Table 3. Consequently, this means that the corrugated paper sheets produced by Stora Enso have lower environmental impact than the one calculated in the initial screening.

The environmental impact caused by corrugated paper sheets produced from 100 % recycled fibres are reduced significantly for some impact categories. For example, the climate change is reduced by 37.9 %.

[6] Personal contact: Fredrik Stensson (Stora Enso)

Table 3. *Decreased environmental impact of the factory when the corrugated paper sheets are produced with 100 % recycled materials compared to 100 % virgin materials, which is the reference scenario with 300 000 VR glasses from the initial screening.*

Impact category	Decreased environmental impact
Climate change	37.9 %
Acidification	5.5 %
Eutrophication	39.3 %
Depletion of abiotic resources - fossil fuels	0.0 %
Depletion of abiotic resources, elements - ultimate reserves	0.0 %
Freshwater aquatic ecotoxicity	1.6 %
Marine aquatic ecotoxicity	4.1 %
Terrestrial ecotoxicity	4.2 %
Human toxicity	7.6 %
Ozone layer depletion	0.0 %
Photochemical oxidation	21.4 %

Lenses

The processes that contribute the most to the environmental impact in all of the impact categories during the production of the lenses are the production of PMMA and injection moulding. Since the number of reports about injection moulding of PMMA were low, this section only focuses on the production of PMMA.

PMMA is an acrylic plastic that have a lot of preferable properties such as a high mechanical strength, stability of colors and good optical properties. Some of these properties make this plastic suitable in lenses (Bruder, 2013). The manufacturing of PMMA starts with a polymerizing of methyl methacrylate (MMA), which produces small granulates that can be formed into desirable shapes (Plastics Europe, 2017a).

The raw material needed for the production of PMMA origins from fossil feedstocks. However, there are a lot of ongoing research today on how to produce plastic from biobased materials in order to decrease the environmental impact. Arkema, a company specialized in advanced chemical products, has developed PMMA that to some extent is produced from a renewable feedstock, namely sugar plants. Production of this type of plastic reduces the carbon footprint[7] compared to PMMA produced from fossil feedstocks. Additionally, the company claims that there are no differences in the properties of the two plastics (Biron, 2017; Arkema, 2017). The only production process available in Ecoinvent was the manufacturing of PMMA from fossil feedstocks, which makes it difficult to assess to what extent the environmental impact can be reduced if the plastic was produced from sugar plants instead.

Another aspect obtained from the literature study is that PMMA is 100 % recyclable, which means that is has huge potential to save fossil feedstocks and natural resources (Plastics Europe, 2017a). The lenses are the main contributor (by approximately 90 %) to depletion of fossil fuels according to the results from the initial screening, as can be seen in Figure A4 in Appendix III. This means that the overall depletion of fossil fuels for the factory has the potential to decrease a lot if the lenses are produced from recycled PMMA. However, recycled PMMA was not available in Ecoinvent and a quantification on how much the environmental impact could decrease using recycled PMMA could therefore not be performed.

[7] The amount of GHGs released into the atmosphere as a result of direct and indirect human activities, such as the manufacturing of products and electricity (National Geographic, 2017).

Racks

The process that contributes the most to the environmental impact in all the impact categories during the production of racks was the production of PS. This plastic is produced when the fossil monomer, styrene, is polymerized. To obtain the final plastic product, either thermoforming or injection moulding can be used to form PS into the desired shape (Plastics Europe, 2017b). The racks will probably be produced by using vacuum forming, which is similar to thermoforming. However, vacuum forming was not available in the database and thus thermoforming was used instead.

The production of racks is the second largest contributor to the depletion of fossil fuels, as can be seen in Figure A4 in Appendix III. A way of decreasing this environmental impact could be to recycle PS, which in turn would decrease the extraction of fossil oil. However, PS is not recycled nowadays and the reason for this is that new recycling processes need to be developed, which require high investment costs (Plastics Europe, 2017b). This is therefore a parameter that can not be changed in order to reduce the environmental impact of the factory at this point.

Another potential way to decrease the environmental impact would be to replace PS with more environmental friendly alternatives that have similar properties. Swedish researchers have developed a bioplastic material called *Cellufoam*, consisting only of wood based raw materials that has the potential to replace PS in many different products, such as in packaging products. This material is produced entirely from nanocellulose and some examples of its properties are that it is highly absorptive and biodegradable (Cellutech, 2017; Callahan, 2016). If the racks instead were produced from Cellufoam, the environmental impacts in all categories would most likely decrease. However, this is a material in its early development phase and it is thus not possible to perform calculations on how much the environmental impact might decrease.

Another material that might decrease the environmental impact is polylactic acid (PLA). It is a renewable plastic produced from corn starch or sugar cane and has similar properties as PE, polypropylene (PP) and PS. One benefit of PLA is that there is no need for new investments in form of manufacturing equipment since it can be produced with already existing production systems for plastics derived from fossil resources. Another advantage of PLA compared to PS is that it can be recycled. From an environmental point of view, recycling PLA is up to 50 times better than other types of end of life treatments, such as composting and landfilling (Slijkoord, 2015; Creative Mechanisms, 2017).

The racks do not necessarily have to be produced from plastics. Another alternative would be to produce the racks from corrugated paper made out of recycled fibres. Calculations on how the environmental impact changes as the racks are produced from PLA or corrugated paper instead of PS were performed in openLCA and those results are presented in Table 4. In the case with corrugated paper, the number of racks was assumed to be 500 instead of 300 due to a predicted shorter lifetime. As can be seen, there are some possible environmental savings when changing the material of the racks. However, the largest environmental savings occurs when the racks are produced from corrugated paper (with recycled fibres) compared to PLA. Additionally, the environmental impact for eutrophication increases in the case with PLA.

Table 4. *Decreased environmental impact of the factory when the racks are produced from PLA and corrugated paper (with recycled fibres) instead of PS, which is the reference scenario with 300 000 VR glasses from the initial screening. For the reference scenario and the case with PLA, the number of racks was 300 whereas the number of racks was assumed to be 500 in the case with corrugated paper.*

Impact category	Decreased environmental impact	
	PLA	Corrugated paper
Climate change	1.2 %	39.5 %
Acidification	2.1 %	7.6 %
Eutrophication	Increases by 0.2 %	40.2 %
Depletion of abiotic resources - fossil fuels	5.8 %	5.8 %
Depletion of abiotic resources, elements - ultimate reserves	0.4 %	0.4 %
Freshwater aquatic ecotoxicity	4.7 %	6.6 %
Marine aquatic ecotoxicity	4.1 %	8.3 %
Terrestrial ecotoxicity	0.1 %	4.9 %
Human toxicity	0.3 %	8.0 %
Ozone layer depletion	0.5 %	1.0 %
Photochemical oxidation	2.1 %	23.6 %

The number of racks in the case with corrugated paper (with recycled fibres) is an uncertain parameter, and therefore further calculations were performed for this scenario. This was done to see how many racks that can be produced from corrugated paper and still be environmentally beneficial compared to the reference scenario (300 racks produced from PS). The calculations were performed for 800, 1 500 and 10 000 racks.

The results from these calculations show that when the number of racks is 800 and 1 500 the environmental impact decrease in all impact categories. On the other hand, when 10 000 racks is used the environmental impact increase (with 1.4 %) for the ozone layer depletion. However, the environmental impact for other impact categories was still significant at this point with, for example, a 38.8 % reduction in climate change compared to the reference scenario. This is also presented in Table 5.

Table 5. *Decreased environmental impact of the factory when the racks are produced from corrugated paper (with recycled fibres) instead of PS and the number of racks are 800, 1 500 and 10 000.*

Impact category	Decreased environmental impact		
	800 racks	1 500 racks	10 000 racks
Climate change	39.5 %	39.4 %	38.8 %
Acidification	7.6 %	7.6 %	7.4 %
Eutrophication	40.2 %	40.2 %	39.7 %
Depletion of abiotic resources - fossil fuels	5.8 %	5.8 %	5.8 %
Depletion of abiotic resources, elements - ultimate reserves	0.5 %	0.4 %	0.3 %
Freshwater aquatic ecotoxicity	6.6 %	6.6 %	6.6 %
Marine aquatic ecotoxicity	8.4 %	8.4 %	8.3 %
Terrestrial ecotoxicity	4.8 %	4.8 %	4.5 %
Human toxicity	8.0 %	8.0 %	7.9 %
Ozone layer depletion	1.0 %	0.9 %	Increases by 1.4 %
Photochemical oxidation	23.6 %	23.6 %	23.4 %

Rotation press

The processes that contribute the most to the environmental impact in all of the impact categories during the production of the rotation press are:

- Production of glued laminated timber
- Production of aluminum

Glued laminated timber is a construction material consisting almost entirely of spruce. This raw material is planed into laminations, which thereafter are put together into the finished material. Glued laminated timber is stronger than steel, compared to its own weight, which makes it preferable to use as a construction material for different purposes. The production of this material does not require much energy compared to production of other construction materials, which is one reason for why it is difficult to find more environmentally friendly alternatives (Glulam of Sweden, 2017).

Sustainable forest management is an approach used by various organizations where factors in focus are preserving biodiversity, prevent deforestation and meeting the society's needs. Sweden is in the forefront regarding this approach, where one example is that the replantation rate is higher than the rate of harvesting. This measure results in large benefits for the environment, both in terms of captured CO_2 emissions but also that this resource is preserved for future generations (Swedish Forest Agency, 2017; Food and Agriculture Organization of the United Nations, 2017). In the calculations performed in the initial screening, the data used for the glued laminated timber production were European average and not specifically for Sweden since that was not available in Ecoinvent. The environmental impact caused by the rotation press might decrease if the calculations were performed with Swedish data instead.

Aluminum is made out of bauxite, which is mined from ores in tropical and subtropical areas. The bauxite ore consists of aluminum that is extracted and thereafter transformed into alumina using the Bayer method (The Aluminum Association, 2017a). The production of pure aluminum from primary raw materials is highly energy demanding. However, aluminum is 100 % recyclable and the recycling process is way less energy demanding (almost 95 % less energy demanding), and is thus preferable compared to primary aluminum (eia, 2012; The Aluminum Association, 2017b; Totten, 2003). However, only primary aluminum was available in Ecoinvent when performing the calculations in the initial screening. The decrease of the environmental impact could thus not be quantified.

Eton Systems transporter

The Eton Systems transporter is the last critical area that was identified in the initial screening. It is mainly made out of:

- Steel
- PC
- Aluminum

The production of the latter has been elaborated in the section about the rotation press above and is thus not further assessed in this section. Below, a description of the production process of steel and PC are presented respectively including alternative ways of producing them.

The Eton Systems transporter contains of approximately 64 % steel which means that it is highly interesting to look further into the production process of steel to investigate if there are any possible ways to reduce its environmental impact. The most common production process (approximately 70 % of all steel produced today) is through a Blast Furnace – Basic Oxygen Furnace (BOF), which was used in the initial screening. This method requires about 600 kg of coke to produce one tonne of steel, which means that approximately 770 kg of coal is required. Another production process of steel is the Electric Arc Furnace (EAF), which only require 150 kg of coal for the same amount of steel. The reason for the lower amount of steel is that it can use scrap instead of virgin material. Consequently, this process is mainly used during recycling of steel (World Coal Association, 2017).

The amount of coal used in the production process is of importance for the environmental impact since it affects the depletion of abiotic reserves. To what extent this impact category is reduced by a change from the BOF process to the EAF process is, however, not possible to assess in this project since the last mentioned is not available in Ecoinvent. Additionally, it is not possible to say whether the EAF process increases or decreases the environmental impact in the other impact categories without further assessments.

Another material in the Eton Systems transporter is PC, which makes up for approximately 4 % of the total weight of the system. This type of plastic can be produced in various ways, one of which is through a polymerization process between bisphenol A (BPA or Bis-A) and phosgene. This process has for a long time been the most commonly used one, but today it is becoming more and more restricted worldwide partly due to the toxicity of phosgene. Phosgene free processes exists, where one example is through a transesterification of diphenyl carbonate (DPC) and bisphenol A (Guichon Valves, 2017). The phosgene free processes have been of interest in many industries since it is more environmentally friendly (Woo et al., 2000). This is due to three aspects, namely the low amount of solvents needed, no phosgene is used and less hazardous by-products are formed. However, these processes require more energy due to higher temperatures (Zhang, 2014). Additionally, the phosgene free processes are not environmentally friendly since they contain BPA, which is toxic. Processes to manufacture PC from renewable materials are therefore under development. One example is by using CO_2 as a monomer in the polymerization, which is of high interest since it for instance is present as waste in many industrial processes. However, the plastic produced through this process does not have the same properties as the one produced from the conventional process, which means that there is a need for more research before this type of plastic can be used commercially (Winkler et al., 2014).

The PC used in the initial screening is not produced from renewable resources, which means that in the future it might be possible to decrease the environmental impact caused by the production of PC for the Eton Systems transporter. However, that is not possible to assess in more detail in openLCA due to the lack of PC produced from renewable resources in Ecoinvent.

Total savings

Throughout the first part of the detailed assessment, several possible improvements for each of the five critical areas have been presented. Some of these changes were not possible to apply in openLCA due to the lack of data in Ecoinvent. However, some changes were possible to test and those results were presented in Table 3-4. The possible reduction of the environmental impact for each impact category are presented in Table 6 as the following changes have been made:

- Corrugated paper sheets produced from recycled fibres
- Racks (increased number of racks with 200) produced from corrugated paper, which in turn are produced from recycled fibres

Table 6. *Decreased environmental impact in the factory as some changes discussed in this section have been implemented. The change is compared to the reference scenario, which is the case with 300 000 VR glasses from the initial screening.*

Impact category	Decreased environmental impact
Climate change	39.5 %
Acidification	7.6 %
Eutrophication	40.2 %
Depletion of abiotic resources - fossil fuels	5.8 %
Depletion of abiotic resources, elements - ultimate reserves	0.4 %
Freshwater aquatic ecotoxicity	6.6 %
Marine aquatic ecotoxicity	8.4 %
Terrestrial ecotoxicity	4.9 %
Human toxicity	8.0 %
Ozone layer depletion	1.0 %
Photochemical oxidation	23.6 %

In the same way as in the initial screening, critical areas for this scenario could be identified. In this case, only four critical areas were identified and those are listed below. The reason for only selecting four areas is that these were much more dominating than the other areas.

- Lenses
- Corrugated paper sheets
- Rotation press
- Eton Systems transporter

An important observation is that the corrugated paper sheets are still a critical area even though it is produced from 100 % recycled materials in this scenario. Additionally, the racks are no longer critical, which were anticipated since the material was changed from a virgin fossil material to a recycled renewable material.

4.2.2 Alternative volumes

During the scenario analysis, the amount of produced VR glasses was varied and the results are presented in this section. The different scenarios are listed below.

- Scenario 1: 75 % of 300 000 visitors wants to run the factory per year
- Scenario 2: 50 % of 300 000 visitors wants to run the factory per year
- Scenario 3: 25 % of 300 000 visitors wants to run the factory per year

The decreased environmental impact for each impact category in scenario 1, 2 and 3 compared to the reference scenario is presented in Table 7. It is clear that there are significant environmental savings possible if the amount of produced VR glasses are reduced. The decreased environmental impact for human toxicity and terrestrial ecotoxicity are, however, not as significant as for the other categories.

Table 7. *Decreased environmental impact of the factory when the volume of produced VR glasses are reduced compared to the reference scenario, which is the case with 300 000 VR glasses from the initial screening.*

Impact category	**Decreased environmental impact**		
	Scenario 1	**Scenario 2**	**Scenario 3**
Climate change	24.0 %	48.0 %	72.1 %
Acidification	23.1 %	46.8 %	69.3 %
Eutrophication	23.9 %	47.8 %	71.7 %
Depletion of abiotic resources - fossil fuels	22.7 %	45.4 %	69.7 %
Depletion of abiotic resources, elements - ultimate reserves	20.6 %	41.2 %	61.7 %
Freshwater aquatic ecotoxicity	23.2 %	46.5 %	69.7 %
Marine aquatic ecotoxicity	21.3 %	42.7 %	64.1 %
Terrestrial ecotoxicity	9.3 %	18.7 %	28.0 %
Human toxicity	4.5 %	9.1 %	13.6 %
Ozone layer depletion	24.1 %	48.3 %	72.5 %
Photochemical oxidation	21.9 %	43.9 %	65.8 %

4.2.3 Alternative dimensions

This part of the detailed assessment was about assessing how much the environmental impact would have changed if other dimensions of the lenses, racks and corrugated paper sheets were used respectively.

Lenses
The scenarios assessed in this part are listed below.

- Scenario 1: Two separate lenses with a diameter of 25 mm (9 g), stored in a corrugated board box with the dimensions of 60*30*10 mm (1.4 g)
- Scenario 2: Two separate lenses with a diameter of 34 mm (17 g), stored in a corrugated board box with the dimensions of 60*30*10 mm (1.4 g)

The environmental impact in scenario 1 decreases when the weight of the lenses is reduced from 10 g to 9 g. On the other hand, the environmental impact in scenario 2 increases, and the reason for this is that the weight of each lens increases from 10 g to 17 g. These results are presented in Table 8.

From a strictly environmental point of view it is most beneficial to use lenses with a diameter of 25 mm that are separated from each other. It is, however, important to point out that both scenario 1 and 2 are more technically difficult to apply in reality which must be taken into consideration during the choice of the dimensions for the lenses.

Table 8. *Decreased environmental impact of the factory when other dimensions are used for the lenses compared to the reference scenario, which is the case with 300 000 VR glasses from the initial screening.*

Impact category	**Decreased environmental impact**	
	Scenario 1	**Scenario 2**
Climate change	2.8 %	Increases by 27.1 %
Acidification	7.9 %	Increases by 56.5 %
Eutrophication	3.2 %	Increases by 29.3 %
Depletion of abiotic resources - fossil fuels	9.0 %	Increases by 63.2 %
Depletion of abiotic resources, elements - ultimate reserves	7.5 %	Increases by 53.8 %
Freshwater aquatic ecotoxicity	8.8 %	Increases by 62.3 %
Marine aquatic ecotoxicity	7.9 %	Increases by 55.9 %
Terrestrial ecotoxicity	1.1 %	Increases by 9.4 %
Human toxicity	0.5 %	Increases by 4.8 %
Ozone layer depletion	0.3 %	Increases by 11.7 %
Photochemical oxidation	5.5 %	Increases by 41.8 %

Racks
For the racks, three scenarios were tested with different dimensions, listed below.

- Scenario 1: 600*400*200 mm (which makes it possible to have four racks on the ground floor of an EU-pallet) with a thickness of 2 mm that equals to a weight of 1.8 kg.
- Scenario 2: 600*800*200 mm (which makes it possible to have two racks on the ground floor of an EU-pallet) with a thickness of 2 mm that equals to a weight of 2.5 kg.
- Scenario 3: 300*400*200 mm (which makes it possible to have eight racks on the ground floor of an EU-pallet) with a thickness of 1 mm that equals to a weight of 0.5 kg.

There are quite small reductions in the environmental impact, as Table 9 shows. The dimensions of the racks are thus not of high importance, which means that the choice of dimensions should be done based on other parameters than environmental considerations, such as technical feasibility, instead.

Table 9. *Decreased environmental impact of the factory when other dimensions of the racks are used compared to the reference scenario, which is the case with 300 000 VR glasses from the initial screening.*

Impact category	Decreased environmental impact		
	Scenario 1	Scenario 2	Scenario 3
Climate change	0.1 %	0.6 %	0.8 %
Acidification	0.2 %	0.8 %	1.1 %
Eutrophication	0.1 %	0.4 %	0.5 %
Depletion of abiotic resources - fossil fuels	0.6 %	2.2 %	2.9 %
Depletion of abiotic resources, elements - ultimate reserves	0.0 %	0.1 %	0.2 %
Freshwater aquatic ecotoxicity	0.5 %	1.9 %	2.5 %
Marine aquatic ecotoxicity	0.4 %	1.6 %	2.1 %
Terrestrial ecotoxicity	0.1 %	0.3 %	0.3 %
Human toxicity	0.0 %	0.2 %	0.2 %
Ozone layer depletion	0.1 %	0.4 %	0.6 %
Photochemical oxidation	0.2 %	0.8 %	1.1 %

Corrugated paper sheets

When changing the dimensions from 600*400 mm to 600*350 mm of a corrugated paper sheet, the environmental impact decreases in all impact categories, as can be seen in Table 10. The result shows that it is beneficial from an environmental point of view to choose a corrugated paper sheet with smaller dimensions. The decreased impact is, however, near 0 % in some of the categories.

Table 10. *Decreased environmental impact of the factory when other dimensions of the corrugated paper sheets are used compared to the reference scenario, which is the case with 300 000 VR glasses from the initial screening.*

Impact category	Decreased environmental impact
Climate change	7.2 %
Acidification	1.4 %
Eutrophication	6.8 %
Depletion of abiotic resources - fossil fuels	0.1 %
Depletion of abiotic resources, elements - ultimate reserves	0.6 %
Freshwater aquatic ecotoxicity	0.5 %
Marine aquatic ecotoxicity	0.7 %
Terrestrial ecotoxicity	1.8 %
Human toxicity	1.4 %
Ozone layer depletion	8.8 %
Photochemical oxidation	3.5 %

4.2.4 Alternative layouts of the lens line

This part of the detailed assessment was about assessing how much the environmental impact would change if alternative layouts, listed below, of the lens line were used instead. The results from the three different scenarios are presented in Table 11.

- Scenario 1: The transportation of the lenses from the Scara robot to the output of lenses is currently performed by an Eton Systems transporter with a weight of 250 kg. This scenario looked into a system with smaller dimensions of the transporter so that its weight was reduced to 180 kg, which was reasonable according to Tomas Nordlund[8] at Eton Systems.

- Scenario 2: This scenario was looking into a situation where the Scara robot and the Eton Systems transporter were replaced by an IRB 1410 robot, provided by ABB. The IRB 1410 robot has higher reach and payload than the robots used in both the first and second production line. That was considered important since the distance from the racks to the output of lenses requires a larger reach of the robot. The weight of the IRB 1410 robot (225 kg) is thus higher than other robots used in the reference scenario (ABB, 2016).

- Scenario 3: Instead of having the lens line, this scenario looked at a situation where the lenses are stored in corrugated board boxes (100*30*10 mm, 3.2 g) within a vending machine. The visitor can obtain their lenses by scanning the QR code on the corrugated paper sheet.

Scenario 1
The environmental impact decreases in all impact categories except for one when the weight of the Eton Systems transporter is reduced from 250 kg to 180 kg. This can be observed in Table 11.

Scenario 2
When replacing the Eton Systems transporter and the Scara robot with an IRB 1410 robot, the environmental impact only decreases significantly in two of the impact categories, which can be seen in Table 11. Additionally, the environmental impact increases slightly in some of the impact categories and remained close to zero in others. This means that the changes in scenario 2 would not result in any significant improvements of the environmental performance of the factory.

Since the choice of the IRB 1410 robot was not suggested by an expert, its weight is a factor with a high uncertainty. Therefore, another robot with approximately half the weight of the IRB 1410 robot was tested to see how much the weight of the robot affects the environmental impact, but the changes in the results are negligible.

Scenario 3
When the whole lens line is replaced with a vending machine, the environmental impact decreases in some impact categories but increases in others, as can be seen in Table 11. This means that removing the lens line and replacing it with a vending machine might not be optimal.

[8] Personal contact: Tomas Nordlund (Eton Systems)

Table 11. *Decreased environmental impact in the factory when changing the layout of the lens line compared to the reference scenario, which is the case with 300 000 VR glasses from the initial screening.*

Impact category	**Decreased environmental impact**		
	Scenario 1	**Scenario 2**	**Scenario 3**
Climate change	0.1 %	0.1 %	Increases by 1.3 %
Acidification	0.1 %	0.2 %	1.4 %
Eutrophication	0.2 %	0.6 %	Increases by 0.7 %
Depletion of abiotic resources - fossil fuels	0.1 %	0.2 %	0.8 %
Depletion of abiotic resources, elements - ultimate reserves	1.6 %	5.8 %	7.4 %
Freshwater aquatic ecotoxicity	0.1 %	Increases by 0.7 %	0.5 %
Marine aquatic ecotoxicity	0.4 %	Increases by 1.0 %	4.0 %
Terrestrial ecotoxicity	6.8 %	23.6 %	30.1 %
Human toxicity	8.8 %	30.4 %	39.6 %
Ozone layer depletion	Increases by 0.1 %	Increases by 0.2 %	Increases by 2.5 %
Photochemical oxidation	0.4 %	Increases by 0.2 %	2.8 %

4.2.5 Alternative press

The last part in the detailed assessment was to look at a different type of press and calculate how much the environmental impact changes.

When the rotation press is replaced with a flatbed die-cutter, the environmental impact changes as Table 12 shows. There are no clear environmental benefits from changing the press since there is an increase of the environmental impact in some impact categories and a decrease in the others.

However, the result is relatively uncertain due to mainly two factors. The first one is that there is already a lot of uncertainty regarding the rotation press since all of its data are assumptions (approved by Johan Bengtsson who is a project manager though), as mentioned in 3.2.5. Secondly, there are a lot of uncertainties when estimating the weight of a non-existing flatbed die-cutter prototype press even though the estimations were made by the project managers who have good insight in the technical aspects of the factory.

Table 12. *Decreased environmental impact in the factory when the rotation press is replaced with a flatbed die-cutter press.*

Impact category	Decreased environmental impact
Climate change	0.0 %
Acidification	0.1 %
Eutrophication	0.0 %
Depletion of abiotic resources - fossil fuels	0.0 %
Depletion of abiotic resources, elements - ultimate reserves	Increases by 0.7 %
Freshwater aquatic ecotoxicity	0.0 %
Marine aquatic ecotoxicity	0.5 %
Terrestrial ecotoxicity	Increases by 3.0 %
Human toxicity	Increases by 3.8 %
Ozone layer depletion	Increases by 0.1 %
Photochemical oxidation	0.3 %

4.3 Sustainable digitalization in the literature

This part of the report presents the result from the literature review of sustainable digitalization. 29 reports were covered in total and the result from the literature review can be seen below, which is presented in the same order as the questions in Section 3.3. A list of all 29 reports, together with the specific sustainability dimension(s) covered by the reports, can be found in Appendix IV.

Some of the covered reports refer to other studies. Those studies are not covered in this master thesis but might be of interest for the reader of this report. Some examples of reports that refer to additional reading are listed below.

- The game-changing potential of digitalization for sustainability: possibilities, perils, and pathways (Seele et al., 2017)
- ICT Innovations for Sustainability (Hilty et al., 2015)
- The Fourth Wave of Digitalization and Public Transport: Opportunities and Challenges (Davidsson et al., 2016)

Most of the reports written in Swedish are published by *the Digitisation Commission*[9] and *the Government Offices of Sweden*[10]. However, the reports written by authors from other countries are published from more various sectors and organizations, for example by consulting companies and scientists.

It was relatively difficult to find reports on the topic of sustainable digitalization, but those that were found cover different dimensions of sustainability. A percentage distribution of how many of the reports that cover each dimension is presented in Table 13.

[9] In Swedish: Digitaliseringskommissionen
[10] In Swedish: Regeringskansliet

Table 13. *The percentage distribution of how many of the reports that cover each dimension of sustainability in the literature review.*

Dimensions of sustainability	Percentage distribution
Economic perspective	90 %
Social perspective	59 %
Environmental perspective	45 %

There are 6 topics that occur more frequently than others in the 29 reports that were studied during the literature review. Those are listed and further described below. Since only one of these 6 topics cover the environmental dimension, a short presentation of some other important topics regarding this dimension are described as well.

- Information and Communication Technology (ICT)[11]
- Increased competence required
- Requirement of new business models
- Development of new ways of learning in the school systems
- The importance of integrity for industries and individuals
- Development of tools to handle data

The economic dimension of sustainability is covered to a large extent in the reports. The most common discussion point in the reports is the importance of developing new *business models*, which is, for example, covered by Larsson (2015). This is discussed as an important part for the industries because digitalization will most likely lead to other demands from the customers and it is therefore a need to develop new business models that can fit these demands. This is seen as an obstacle for the industries since they might not have a suitable knowledge on how to make these changes. Another topic that is covered is the need for industries to *increase the competence* of the employees (also described in Section 2.2.3). According to the literature, this is an important obstacle for the industries and has to be solved in the near future. Another topic that is highlighted in the economic dimension is the importance of developing systems that can prevent *integrity* issues. That is of importance since many processes will be connected to internet and this can cause integrity issues if personal information about the industries is illegally collected. Both of these topics (competence and integrity) are connected to the social dimension as well, which is further described below. The last aspect that is under discussion is that *tools* needs to be developed in order to handle the large amount of data that is predicted to increase as the industries becomes more digitalized.

The social dimension of sustainability is covered by a bit more than half of the reports. The main conclusions from these reports are that more competence is required in the future and that the *school systems* needs to be developed. Such a development could, for example, be to use more digital equipment. The reports also highlight the issue of integrity because it is predicted that many industries will collect information about individuals in the future to give more personal advertisements. In this case, new systems needs to be developed in order prevent integrity concerns for individuals, such as illegal use of personal information. An example of a report that covered most of these aspects is the one written by Konsumentverket (2016).

The last dimension of sustainability, the environmental, is covered in slightly less than half of the reports. One topic that is covered to a large extent in the environmental dimension by, for example, Höjer et al. (2015) is *ICT*, where it is discussed whether ICT can facilitate or

[11] Briefly defined as all technologies and software that facilitate the use of the digital world (Lunds tekniska högskola, 2017).

counteract an environmentally friendly digitalization. It is stated that ICT has the possibility to reduce the environmental impact of different production processes but it is also stated that it might increase the environmental impact if it is used and handled in the wrong way. An example of such an increase is if the disposal of the ICT products are done in a way that causes negative effects on the environment. Some other discussion points in these reports are the importance of increasing the efficiency in the production and the use of renewable material. This is discussed in the sense that it is important to save the natural resources as the society becomes digitalized. In addition to this, many reports also present three different types of effects, namely direct-, enabling- and systems effects (also described in Section 2.2.4). These effects describe different levels at which environmental impact can occur. All of these aspects are covered in the report written by Gustafsson et al. (2016).

Another important observation from the literature study is that some of the authors of the reports mention topics that they think require further studies. An example is the report written by Höjer et al. (2015) where the authors suggest that further studies are needed on how ICT can be used to reduce the environmental impact caused by consumption and on how digitalization affects integrity and security.

5. Discussion

This section includes a discussion about relevant parts of the master thesis. Firstly, it highlight reflections on the methodological choices made throughout the thesis. Secondly, the results obtained during the initial screening, detailed assessment and literature review are discussed. Lastly, some recommendations for further studies are suggested.

5.1 Methodological choices

This section is divided into three parts, all of which corresponds to the three objectives stated in Section 1.3. LCA was used as a method in both the initial screening and the detailed assessment, but it is only discussed in the section about the initial screening since it was used to a larger extent in that part.

5.1.1 Initial screening

LCA

LCA was chosen as an appropriate tool to use in order to conduct this master thesis for several reasons. For example, it gives a holistic view over the life cycle of a product and service. Additionally, the outcome from an LCA is easy to understand for people that are familiar with this tool. This is, however, not as simple for those who are unfamiliar with LCA since the meaning of different concepts, such as GWP and eutrophication, might be difficult to understand. A discussion about the use of other tools is therefore provided below.

There are several other tools that could have been used instead of LCA for conducting this study. Another alternative would have been to use Material Flow Analysis (MFA)[12] in combination with indicators. That would, however, have been problematic for various reasons. Firstly, in MFA the flow of a certain material is assessed within defined system boundaries. That would be problematic for this study since there is not one single material that is assessed, but rather several flows of materials, such as corrugated paper, PMMA and steel. Performing

[12] A method where material and energy balances are performed over a defined system with the aim at quantifying the flows and stocks within the system boundaries (OECD, 2008).

an MFA for all of these materials would thus be too time consuming and hard to interpret. Another issue with this combination of tools is that the choice of indicators requires subjective decisions in the sense that the indicators would have to be selected by the authors of this report. The use of LCA is beneficial because it is easier to look at several material flows simultaneously and it is possible to minimize subjective decisions.

Another tool that could have been used in this study is carbon footprint. The consequence of such a choice of tool would have been that only one impact category would have been accounted for. In comparison to this LCA study, that would have been an incomplete study. On the other hand, it might have been easier to communicate the results to those responsible for Smart Factories at Universeum since climate change is relatively familiar to most people. For example, the results could easily have been translated into the number of laps around the globe with a car. However, an LCA includes more impact categories, and thus more emissions, and therefore provides a broader perspective.

In general, conducting a detailed LCA is very time consuming, which is one of the largest constraints for many organizations. One time consuming step in LCA is the data collection, which was realized in this study because a lot of time were assigned to this step before the calculations could be performed. The main reason for why a lot of time was spent on the data collection was the difficulty to get in touch with the contacts provided by the project managers. Additionally, some of these contact did not have the right data. A lot of assumptions were therefore taken that in turn affected the reliability of the results, which is further discussed in the sections below. In addition to this, it would be beneficial if the project managers would have been more informed about what type of data that is needed in order to conduct an LCA because this would certainly limit the time spent on the data collection.

It was found, when collecting the data, that not all components were available in Ecoinvent and therefore some of these were assumed to be produced from a similar material or manufacturing method. If time would not have been a limiting factor, an even more detailed data collection could have been performed where data from other sources than Ecoinvent could have been used. A more detailed and reliable result would in that case be obtained.

Choices made in the LCA

Throughout the report, several choices have been made. This section highlights some of the more critical choices made in connection to the LCA.

A functional unit of “X number of VR glasses produced per year” (where the “X” refer to 300 000 and 30 000 respectively) was used in this study. The reason for choosing two variants of the functional unit was that the factory will only be located at Universeum during approximately two years and thereafter moved to Lindholmen with significantly less visitors. The choice of functional unit affects the analysis in the sense that 300 000 VR glasses are probably a worst case scenario at Universeum.

The geographical boundary used in this study was Europe. The reason for this is that most of the data in Ecoinvent are not available for Sweden specifically. That might reduce the credibility of the results in the sense that there are a lot of uncertainties regarding where the actual production of the components and materials take place. That is valid if the production are located in Sweden for all components and materials. However, since the actual location is an uncertain parameter, it might be more realistic to use a broader system boundary, such as Europe. Choosing an even broader boundary was not considered to be suitable though. It would have been interesting to look further into where the components in the factory are located to get a more accurate result if there was no time restriction of this master thesis.

The assembling of the components within the factory is not included in this study. This is because information about how the production of the specific components in the factory at Universeum are performed were hard to obtain. The assembling of the components is therefore considered to be negligible in comparison to the production of the different materials needed for the specific components. This is somewhat misleading because more energy and other production systems would have been needed if the assembling would have been included. The environmental impact caused by the components within the factory at Universeum would probably be larger if their assembling is included since it, for example, requires electricity. That might in turn have affected the critical areas. If the master thesis would extend to a longer time period, a more detailed literature research and interviews with experts could have been performed in order to get a more detailed overview about the assembling of the components.

It is important to clearly state in the LCA which impact categories that are assessed. In this study, all impact categories that are available in CML were included in order to avoid subjective prioritization, which leads to higher credibility of the result. However, it might not be so relevant to look at, for example, ozone layer depletion since large improvements already have been made in this area. That is because the ozone layer has recovered in many places where it previously has been depleted to a large extent. Consequently, that impact category is not as high on the agenda over environmental work for many countries, which in turn means that the results from this thesis might be misleading since such categories are included in the selection of the critical areas. However, in turn it might be problematic to make decisions based on studies in which subjective prioritizations have been made. This is because there are a lot of different opinions on which impact categories that are of higher concern and the use of studies applying such a prioritization could thus be difficult to use.

Capital goods are included in this study, which is motivated by the fact that the core of this study is the factory and not a specific product. This means that the production of all the components within the factory must be taken into consideration because they serve the same function, which is to produce a specific amount of VR glasses. In some LCAs, capital goods are not included since such components are used in several production processes during its lifetime and are thus not produced specifically for the assessed product or service. In this thesis, the components are specifically manufactured in order to produce the VR glasses, which makes it reasonable to include them. However, the components might be used for other applications after it has served its purpose in the factory, which creates an allocation problem. How much of the environmental impact of their production should be allocated to our process and how much to future applications? That is a problem that is avoided if capital goods are not included. In this master thesis, it was assumed that the components will not be used for other purposes, which meant that no allocation problems were faced.

The end of life treatment of the waste was excluded in this assessment. The reason for excluding the waste treatment was that it is hard to know how the waste at Hans Andersson recycling and IL recycling are treated. Allocation methods would be necessary to apply if the waste treatment would have been included since a mixture of several types of waste probably undergoes the same treatment. The main reasons for excluding this step of the life cycle are that this master thesis is limited by time and also due to the large uncertainties on how the waste treatment actually will be performed. This decision is therefore considered to reduce the uncertainties of the results obtained in this master thesis.

Assumptions
A lot of different assumptions had to be made in this study and a discussion about the most relevant ones is presented in this section.

The amount of produced racks was assumed to be 300 based on how many lenses that will be transported to Universeum. This is an assumption that might have had a significant impact on the results of the study since it turned out to be one of the critical areas. If an overestimation regarding this assumption was made, it would mean that this area might not be critical, which means that the parts in the detailed assessment concerning the racks would thus not be of relevance anymore.

The maintenance of the factory was assumed to be needed 12 times a year. This is a parameter that probably represents a worst case scenario. The factory at Universeum will be a smart factory, which also includes smart maintenance. That is what one of the 10 master theses within Smart Factories are assessing, performed by Christoffer Hildebrand and Anton Alveflo. Smart maintenance is, according to Christoffer[13], basically about ensuring that components are used as long as possible. This can be done by collecting data and parameters about earlier failures that makes it possible to predict when components require maintenance. Today, many companies replace their components earlier than necessary to prevent stops in the production chain. If maintenance systems could be used and developed, it would mean that early replacement of components could be prevented and they could thus be used during a longer time. In this assessment, it was assumed that the lifetime of the factory would be much shorter than the lifetime of its components and no replacement of those would thus be necessary. That is a reasonable assumption since the factory will apply the concept of smart maintenance. The part of the results that is affected by the maintenance is only the transports. However, the transports give rise to a low share of the environmental impact of the factory and therefore would an even less amount of transports result in lower environmental impact.

A lot of assumptions had to be taken regarding the weight of some of the components in the factory, such as the weight of the rotation press. However, these assumptions were approved by one of the project managers, Johan Bengtsson, which makes them justified. Even though these assumptions were justified, it is important to highlight the fact that some of the critical areas are affected by this type of assumptions. For example, the rotation press is calculated entirely based on weight assumptions, which is problematic since the rotation press will be on a prototype scale in comparison to the ones used in real industries. This means that despite the fact that Johan has approved the assumption, there are still uncertainties regarding its credibility. Such an assumption and calculations thereof is a factor that affects the results and should be kept in mind when looking into the results.

The factory was assumed to be run at full speed for five hours per day at Universeum. The energy consumption of the factory was given to us by one of the project manager for parts of the project, Adrian Bentland. Based on that information and assumption, the annual electricity consumption could be calculated. The production of electricity is a process that might be of more importance if it turns out that the factory will be running at full speed for more than the assumed time. However, Universeum is open eight hours per day and this assumption was thus considered as appropriate but it would be important to evaluate the electricity consumption more in detail if the running time increases.

[13] Personal contact: Christoffer Hildebrand (Master thesis student)

2 %-limit
The critical areas were identified in such a way that the processes in the life cycle that contributed to more than 2 % of the total environmental impact in a certain impact category were noted. Thereafter, the critical areas were chosen as those that occurred most frequently. The reason for choosing the 2 %-limit was that it was important to ensure that the critical areas contributed to a significant part of the environmental impact since those were to be improved in the following part of the master thesis. An advantage of using this method to identify the critical areas is that it reduces subjective prioritizing among the different processes. On the other hand, the critical areas are strongly connected to which limit that were chosen and therefore other areas would have been identified if the limit was changed to, for example, 10 %. In that specific case, the critical areas would instead only be the corrugated paper sheets and the lenses. A consequence of this is that there would have been a slightly different approach in the detailed assessment since all parts that covers the racks, press and Eton Systems transporter would have been excluded. However, this means that the choice of a 2 %-limit gives a more thorough assessment, which should be considered as beneficial.

It is also important to point out that during the selection of critical areas, there was a risk for missing out some relevant processes in the sense that a process could have been dominating in one impact category but negligible in the rest. As a consequence, that process would not have been chosen as one of the critical areas. However, that was carefully looked into during the selection of critical areas in order to ensure that the correct processes were identified as critical areas. Therefore, no significant processes have been left out, which increases the reliability of the result.

The critical areas could, however, have been chosen by using completely different approaches. One example of such an approach is that they could have been chosen based on which parts of the life cycle that were considered as technically easiest to improve. That approach was not chosen for several reasons, for example the fact that it would mean that subjective decisions had to be made, which is something that have been excluded as much as possible in this project. Another way of choosing the critical areas could have been to only select some of the 11 impact categories and look at which processes that dominates in those categories. That would, however, also be based on subjective decisions and were thus not considered as an appropriate method.

Uncertainties of the results and data quality
There are several factors that might give rise to uncertainties in the results. In this study, a lot of assumptions have been made, which clearly affects the results and thus its credibility. Additionally, all data is somewhat estimations since the factory does not exist yet, which makes it difficult to get any precise data. During the initial screening, some decisions were yet not taken (for example the type of Eton Systems transporter), which made it difficult for the providers of the components to give precise data. However, the providers have relatively good insight in their products and could thus give credible estimations based on their experience.

Additionally, there were some changes made in the layout of the factory that were decided after the calculations were performed. An example of such a change is that the application developed for the visitors mobile phones also should be used to start the factory. In practice this means that the ordering station will not consist of displays anymore, which in turn affects the environmental impact of the factory at Universeum. However, the changes made after the calculations were completed would probably not have affected the overall result to any larger extent since the changes only affected parts of the factory that were non-critical.

Another factor that can affect the result of the study is if the software, openLCA, was not used correctly. That is a reasonable source of error since it was the first time this software was used by us. There is thus a risk for errors in the modelling, which could lead to a lower credibility of the results. However, the modelling has been checked by the supervisor at Swerea IVF, Jutta Hildenbrand, who has worked a lot with such software in the past.

Another type of human error that might have occurred in this master thesis is that there can be errors in the calculations performed by hand, which could thus affect the results. However, there are no extensive calculations made, which makes it reasonable to believe that such errors are minor.

5.1.2 Detailed assessment

There are a lot of approaches that can be used when improvements of a process are to be identified. In this study, five approaches were used. One of them, the volume reduction of the number of produced VR glasses, was requested by Johan Bengtsson since the volume of glasses are considered to be an important uncertainty for him. The other approaches were, however, chosen based on what was expected to reduce the total environmental impact of the factory at Universeum. These choices were thus based on prior knowledge of the authors of this report. One way of improving the choice of these methods could therefore be to consult with, for example, the supervisors (Jutta Hildenbrand and Karin Wilson) at Swerea IVF who have more experience and prior knowledge.

5.1.3 Sustainable Digitalization in the literature

The literature review is far from complete in the sense that only 29 papers were covered. That is because there was a limit on how much time that this part of the project could stand for since it is only a minor part of the total project. If more time would have been spent on the literature reveiw, a more detailed result would have been obtained. Additionally, the literature review can be seen as incomplete in the sense that other combinations of search phrase could have been used when reports were searched for in databases. If some key phrases were left out, it means that some reports were not identified. However, the results from our study can still be used as an indication of the available literature and thus act as a starting point for further studies in the topic of sustainable digitalization.

5.2 Results

Some of the results obtained throughout the study are discussed in this section, starting by the critical areas obtained in the initial screening. Thereafter, some of the results from the detailed assessment and literature review are discussed.

5.2.1 Initial screening

The critical areas that were identified with the 2 %-limit approach did not match the expected critical areas. The corrugated paper sheets and the lenses were anticipated to be critical areas due to the large volumes, but the other three critical areas (racks, Eton Systems transporter and rotation press) were more surprising. Instead, the electricity consumption was thought to be an important contributor to the total environmental impact since that is a topic that sometimes is brought up when digitalization is discussed. There might be different reasons for why the electricity consumption resulted in a relatively low impact. One reason could be that Swedish average electricity was used, which in general has a low impact since it is relatively fossil free.

Another reason could be that the factory is on a prototype scale, which means that the components in the factory that require energy are in a smaller scale which might have a lower electricity demand than full-size components.

5.2.2 Detailed assessment

Alternative processes and raw materials
This part of the discussion reflects upon the part of the detailed assessment about the literature study of the production processes and materials used to produce each of the five critical areas. The aim of this part was to see if there are any other materials and/or production processes that could have been used instead of those used in the initial screening.

An important message to the project managers of Smart Factories, and those responsible for similar projects, is to put pressure on the supplier of the corrugated paper sheets to ensure that the use of recycled materials are increased. This message is motivated by the results from the detailed assessment where it was found that the environmental impact can be significantly reduced if recycled materials are used instead of virgin material in the corrugated paper sheets. It was, however, also found that Stora Enso uses a mixture a virgin and recycled material in their products. These results indicates that the results from the initial screening could have been improved if an exact share of virgin and recycled materials was known.

The literature study also reveal that the material used in the lenses (PMMA) is 100 % recyclable, which means that its environmental impact could be reduced if recycled material was used instead of virgin material. That is, however, not possible with today's technique for the producer of the lenses (Fristad Plast) since high purity of the raw material is required in order to obtain lenses of good quality. Nevertheless, this is a factor that might require further studies. The use of recycled raw materials have to increase, perhaps with the help of policy measures that benefit such material choices.

It is difficult to say which material to use for the racks. According to the results from this part of the assessment, PLA and corrugated paper (produced from recycled fibres) are two alternatives that reduces the total environmental impact of the factory. The racks produced from corrugated paper are better from an environmental perspective (taking into consideration that approximately 200 more racks have to be produced). This is also valid if it turns out that such a material choice in the racks require up to approximately 10 000 racks instead of the 300 that would be sufficient for the racks with PS. However, it is important to consider that the racks are used to store lenses that are sensitive to damage, which means that the racks produced with an alternative material needs to be able to meet that demand.

The result show that there are possible improvements for the press as well. For example, virgin aluminum was used in the rotation press during the initial screening, but if produced from recycled materials (reasonable since aluminum has a high recycling rate) the total environmental impact of the rotation press would be reduced.

To conclude this part of the discussion, the choice of material is of importance for both the consumables and the other components in the factory. This is an area where the project managers of Smart Factories could have made an active choice during early stages of the project design. This means that they could have decided that as much equipment as possible should be produced from recycled materials, which in turn would have put pressure on the suppliers to use such materials. As an alternative to this, they could have proposed the reuse of old components instead of new ones.

Alternative volumes
The second part of the detailed assessment was to investigate how much the environmental impact of the factory can be decreased if the produced volume of VR glasses is reduced.

Every single measure to reduce the volume of produced VR glasses should be considered from an environmental perspective. That is because the results from both the initial screening and this part of the detailed assessment reveal that the environmental impact is strongly connected to the volume of produced VR glasses.

The result show that reusing the VR glasses give great benefits from an environmental perspective, even for the scenario with the lowest reuse rate. A recommendation to the project managers is therefore to consider the opportunity to reuse VR glasses next to the factory, both at Universeum but also at Lindholmen.

In a larger perspective, the reuse of products in the society is also an important factor to keep in mind as industries are becoming more digitalized. Some studies reveal that new technologies can increase the production rate. It is, from an environmental point of view, important that the production volume do not increase to such an extent that it counteracts the environmental benefits of the increased efficiencies of the industries. This study is one example of what might happen if there are no considerations taken into this. High production rate of VR glasses makes it possible for larger groups, such as school classes at Universeum, to produce a pair of glasses for each member of the group during a short period of time. The increased efficiency in this case therefore increases the environmental impact of the factory, but if the suggestion to reuse VR glasses is implemented, it can reduce the environmental impact significantly.

Alternative dimensions
The third part of the detailed assessment was about assessing how the environmental impact would change if other dimensions of the racks, lenses and corrugated paper sheets were used. The main result from this assessment is that the alternative dimensions did not result in any major benefits for the environment compared to other improvements assessed earlier in this part of the master thesis.

It is, however, important to discuss this aspect since even small reductions can be significant in the end. From an environmental point of view, it is therefore better to choose the smaller dimension of the components in the factory if there is no explicit need to have the larger dimension. However, if such a change makes it, for example, more expensive to produce the product it might be better to use the larger dimension and instead minimize the environmental impact in other areas.

Alternative layouts of the lens line
The Eton Systems transporter is one of the five critical areas and thus an area that was assessed further. This was done by looking at three different scenarios where the Eton Systems transporter was either eliminated completely or reduced in size.

The result reveal that none of the three scenarios give rise to any significant improvement of the environmental performance. On the contrary, the environmental impact increased in two of the scenarios, which was unexpected. There can be two probable reasons for why these changes did not reduce the environmental impact to a larger extent. The first one is that the Eton Systems transporter is not the main contributor to the total environmental impact of the factory. In other words, the Eton Systems transporter might not have been a critical area if another limit than the

2 % limit was chosen, as discussed in Section 5.1.1. In practice, this means that even though the environmental impact of the Eton Systems transporter is reduced, as in this part of the detailed assessment, it will not affect the total environmental impact to any significant extent. The second reason is that scenario 3 (lens line replaced with a vending machine) require an increased production of corrugated paper since the lenses had to be stored in corrugated board boxes within the vending machine. The increased consumption of corrugated paper give rise to a higher environmental impact. However, that impact could have been reduced if recycled material was used, as discussed in this section under alternative processes and raw materials.

Nevertheless, scenario 1 (reduced weight of Eton Systems transporter from 250 kg to 180 kg) is worth considering because it did in fact give rise to a reduction in the total environmental impact. Even small reductions can be significant in the end and it is therefore better to choose a smaller size of the Eton Systems transporter if this do not affect the function in the factory.

Alternative press
The last part of the detailed assessment was to assess how the choice of press affected the environmental impact. It is from this assessment not clear which press that is best from an environmental perspective.

The flatbed die-cutter increases the environmental impact in some categories but reduces it in others. From an environmental point of view, the choice of press therefore depends on which impact categories that are considered as important and less important by the project managers. Additionally, it is important to point out that there are a lot of uncertainties regarding the results since the data used for both presses are assumptions. For that reason, it is not possible to make a distinct recommendation on which press to choose. This is also why this area is not further discussed in this report.

5.2.3 Sustainable digitalization in the literature

This part of the discussion covers the results from the third part of the project, namely the literature review of sustainable digitalization. After a short discussion about the general result, this section continues with a discussion about the 6 topics (introduced in Section 4.3) that occurred most frequently in the reports. Thereafter, a discussion about topics covered to a less extent is provided. Lastly, a topic that is not covered by the literature review is discussed.

The results from the literature review were relatively surprising since it was not expected that the environmental dimension of sustainability is the one that is covered the least. Instead, it was expected that the social dimension would have gotten less attention compared to the other two dimensions. After the literature review was performed, it was realized that the economic and social dimensions are correlated and are highlighted together in many papers. One example of this is that the industries are facing challenges regarding their level of competence, which is connected to the economic dimension. At the same time, a lack of competence affects the social dimension in the sense that individuals have to actively take on measures to increase their competence so that they are considered as attractive employees.

Business models
The main obstacle for the economic dimension is, according to some of the papers listed in Appendix IV, the development of new business models. In other words, companies today have relatively low level of knowledge on how they should adjust their businesses in order to maintain an economic growth as the society is becoming more digitalized. A suggestion to reduce this obstacle is to develop a standardization that describes how companies can develop

their new business models in a suitable way. This can, for example, be done in Sweden by the Digitisation Commission which is responsible for digitalization issues within the Swedish government. Another way of increasing the digitalization of companies could be through financial incentives. Such policy measures could be beneficial for those companies that actively work with improvement of their digitalization and, for example, could get a discount on taxes in return.

Tools to handle data

Another obstacle highlighted by some papers is the issue of handling the increased amount of data generated as a consequence of digitalization, as described in Section 2.2.2. This is an area where there might be a business opportunity in the sense that a lot of companies will have to increase their ability to handle huge amounts of data in the future, which can be facilitated by hiring experts as consultants in this area.

Competence

As mentioned earlier in this discussion, increasing the competence of employees is considered a major challenge as the society becomes more digitalized. This challenge can be seen from two perspectives, both from a company perspective but also an individual perspective. Starting with the companies, ensuring that they are given the opportunity to provide the relevant education for their current employees can be considered as a key aspect since they might not have high enough competence today. If companies fail to do so, there is a risk that they can not be digitalized to the extent that might be required in the future in order to remain as a competitive company on the market. In turn, this might affect the competitiveness for Sweden on the global market. It is therefore suitable if an education program is developed by, for example, the government, which each company can take part of. A prerequisite for such a program would be to ensure that all companies can afford it.

Making sure that new technologies and jobs are embraced in the society could be a way of ensuring an increased competence in the society. New technologies can facilitate improved ways of learning, for example the use of iPads among young children. If such technologies are allowed to be used by the parents in early ages it can improve the digital competence of those children subconsciously. If parents fail to embrace new technologies, there is a risk that their children have lower prior knowledge than other children when they are starting first grade and thus fall behind their classmates. Taking it one step further it might mean that such students can not receive a university degree in this area of expertise and thus not receive enough competence needed for the more advanced jobs in the future. It is important to highlight the fact that this is only one of many possible factors that contributes to such a problem.

School systems

A prerequisite for young adults to receive the relevant competence is that the school system is developed. That is something that can be difficult with a conservative mindset of the ones responsible for the schools. On the other hand, there is also huge potential for those who succeed in such a development. Examples of changes in the school system could be the use of more technologies, such as YouTube videos or the use of VR glasses, which could benefit the learning ability of some students. Such improvements can, for some students, be seen as a degradation in the sense that all students learn in different ways. Those who prefer to write and draw by hand might have trouble with such an improved school system. A challenge for the schools is thus to find a balance between the use of new and old ways of learning.

Integrity
Another topic that is highlighted in the papers in the literature review is integrity. More and more personal data is collected by companies about their customers and used in, for example, targeted advertising. Such information could also be used in ways that are not appreciated by the customer. It could therefore be important that suitable laws and regulations that restrict the misuse of such information are in place. Information stored by companies, and governments, therefore have to be secured in a suitable manner.

ICT
The use of ICT is discussed in several reports from the literature review as an area that can either facilitate or counteract a sustainable digitalization. For example, Höjer et al. (2015) highlight four main principles on how ICT can be used to facilitate a sustainable digitalization from an environmental point of view. The authors do, however, not say anything about how the use of these principles affects the social and economic dimensions of sustainability. For example, one of the principles (called "Replace") refers to the fact that ICT should be used to replace products, services, travels and transports. That is, by the authors, considered as having a positive effect on the environment. However, it is not clear how such changes affect the social and economic dimensions. A travel company might not appreciate that ICT reduces the need for individuals to travel since that is not desirable for their business, which therefore might affect the economic aspect of sustainability in a negative way.

Except for presenting the four principles, the authors also discuss the importance of applying policy measures to prevent, for example, higher consumption rates. This is also highlighted by, for example, Hilty et al. (2006). According to them, further assessments on how ICT affect the environmental dimension of sustainability are required in order to develop suitable policy measures. It might, however, also be important to ensure that ICT does not counteract any of the other dimensions and assessments about all three dimensions might thus be necessary as well. That was, however, not mentioned specifically in any of the reports and is therefore an area where further assessments are required.

Topics covered to a less extent in the literature review
A topic presented in the result regarding the environmental dimension is that digitalization can lead to opportunities for the industries in the sense that the productivity can increase when the cycle times of the processes decreases. This can lead to increased production volumes which could benefit the industries competiveness on the market. At the same time, digitalization might also make it easier for the consumers to shop online and find what they are looking for in an easier way. However, this could lead to an increased consumption, which in turn can affect the environment in a negative way. This is therefore a question of sufficiency. The combination of efficiency and sufficiency is highlighted by Hilty et al. (2011) where it is stated that any measure that fails to combine these two concepts will lead to unsuccessful results.

Another topic covered in the literature review about the environmental dimension is to ensure that renewable materials are used as much as possible. This can be compared to the results from this master thesis where the material used to produce, for example, the racks was replaced with corrugated paper. The environmental impact of the VR glasses over its life cycle did decrease with almost 40 % in some of the impact categories, even though the number of racks produced from corrugated paper increased to 10 000.

Studies show that a lot of jobs requiring low- or medium educations might disappear from the market in the future as a consequence of the automatisation of many jobs, as described in

Section 2.2.3 and 2.2.4. This topic is also covered in one of the reports in the literature review written by Heyman et al. (2016), which discuss the risk for polarization of salaries. This is an aspect to keep in mind to reduce inequities as the society are becoming more digitalized.

A topic not covered in the literature review

This section highlight a topic that is not covered in any of the reports in the literature review. However, it is mentioned in Section 2.2 and is considered as interesting to discuss.

There are huge inequalities among different countries, as can be seen in the society today. There might be a risk that digitalization increases these inequalities even further. Many of the developing countries have not enough electricity available today and this is a huge challenge since the availability for electricity is a prerequisite for increasing the digitalization. For example, each country in Africa only produces approximately 3 % of China´s annual electricity production. It is from this clear that the electricity grids have to expand in those (and other) developing countries with low availability of electricity in order for them to have the potential to digitalize their industries and thus increase their competitiveness on the global market. From an environmental point of view, it would be beneficial if those countries expand their electricity production without using fossil resources. A huge potential for countries in southern latitudes is to invest in solar cells. However, this is a huge issue of concern because all countries do not have enough competence or knowledge about renewable energy and there is thus a risk that they become fossil dependent instead. International cooperation could therefore be suitable to give developing countries the ability to expand their electricity grid in an environmental friendly way and thus embrace the digitalization.

5.3 Suggestions for further studies

Based on the results from this study, some suggestions for further studies have been developed, which are presented in this section.

- It is not possible to determine whether this factory is more sustainable than a conventional factory since there is no reference scenario to compare with. A comparison between a product manufactured from a digitalized factory and a conventional factory would be appropriate to draw such a conclusion. A suggestion is therefore to perform studies that compare the differences between a digitalized factory and a conventional factory.

- In the results, it was clear that the volume of consumables was the largest contributor to the environmental impact. It is therefore essential to perform further studies about how to keep the consumption rate of products at a sustainable level as the industries becomes more digitalized.

- It was found in the literature review that ICT has the potential to contribute to a sustainable digitalization. However, some studies discuss the risk that ICT might prevent a sustainable digitalization and it is therefore important to conduct more research about how to utilize ICT in a sustainable way.

6. Conclusions

This master thesis cover three main research questions, throughout the report referred to as the first, second and third objective respectively. This section aims at highlighting the main findings regarding these objectives.

First and second objective
The five critical areas identified in the initial screening are the corrugated paper sheets, lenses, racks, rotation press and Eton Systems transporter. There are mainly two ways in which the environmental impact caused by these areas can be reduced. The first one is to reduce the volume of consumables by having a certain number of VR glasses next to the factory that the visitors can borrow. The second one is to ensure that recycled materials are used for the corrugated paper sheets.

Third objective
The literature review show that it is relatively difficult to find literature about sustainable digitalization. The economic and social dimension of sustainable development are covered the most (90 % and 59 % respectively) whereas the environmental dimension is touched upon by less than half of the reports (45 %). The need for increased competence and the lack of standardization of digitalization were two challenges that were highlighted by the literature covered in this study.

7. Recommendations

Since the number of produced VR glasses were shown to affect the environmental impact to such a great extent, it is important to ensure a low consumption of those. A recommendation to the project managers of Smart Factories, and those responsible for similar projects, is to adjust the layout of the factory in the sense that there is a possibility to reuse the glasses in connection to the factory. Additionally, the project managers are also recommended to ensure a high rate of recycled materials in the corrugated paper sheets.

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Figure 4 and 5 were received by its producers, Niclas Busck and Fredrik Svensson, 2017-04-27. Producers are master thesis student involved in Smart Factories.

Appendix I - Data

Table A1. *All data from suppliers, project managers, literature and assumptions used in the calculations. For those parts that have no specific components stated (such as printers, scanners, displays, cameras, sensors and cables), the data was taken directly from Ecoinvent and its specific components were thus not known.*

Processes in the life cycle		**References**
Corrugated paper		
Weight of a corrugated paper sheet	90 g	Richard Hedman
Weight of a pressed sheet	37.91 g	Fredrik Stensson
Waste from the production	5 %	
Measures	600*400 mm	Johan Bengtsson
Lenses		
Material	PMMA	Christian Forsström
Weight	10 g/lens	
Material of the tool used to produce the lenses	Steel	Philip Frifelt Lundqvist
Weight of tool	4 kg	
Diameter of lenses	25 mm	Johan Bengtsson
Measures of the connection of the lenses	5*20 mm	Assumption
Racks		
Material	PS	Christian Forsström
Weight	1 kg/rack	Calculated by hand, see Appendix II
Number of lenses in one rack	100	Christian Forsström
Measures	300*400*200 mm	Johan Bengtsson (200 mm is an assumption though)
Transport from Stora Enso to Universeum		
Truck	Diesel truck, Euro 5	(Wernet et al., 2016)
Distance	60 km	(Eniro, 2017)
Number of sheets per pallet	3750	Richard Hedman
Number of pallets per transport	4	
Weight per pallet	22 kg	(Malmö Pall AB, 2017)
Cargo	1.45 ton/transport	Calculated by hand, see Appendix II
Number of transports	20 transports/year, 300 000 VR glasses	

	2 transports/year, 30 000 VR glasses	
Transport from Fristad Plast to Unvierseum		
Truck	Diesel truck, Euro 5	(Wernet et al., 2016)
Distance	78.7 km	(Eniro, 2017)
Cargo	0.23 ton/transport	Calculated by hand, see Appendix II
Number of transports	30 transports/year, 300 000 VR glasses 3 transports/year, 30 000 VR glasses	Johan Bengtsson
Transport from Universeum to Fristad Plast		
Truck	Diesel truck, Euro 5	(Wernet et al., 2016)
Distance	78.70 km	(Eniro, 2017)
Cargo	0.13 kg/transport	Calculated by hand, see Appendix II
Number of transports	30 transports/year, 300 000 VR glasses 3 transports/year, 30 000 VR glasses	Johan Bengtsson
Transport from Stora Enso to IL Recycling		
Truck	Diesel truck, Euro 5	(Wernet et al., 2016)
Distance	20 km	(Eniro, 2017)
Cargo	150 kg/transport	Assumption
Number of transports	9 transports/year, 300 000 VR glasses 1 transport/year, 30 000 VR glasses	Calculated by hand, see Appendix II
Transport from Universeum to Hans Andersson Recycling		
Truck	Diesel truck, Euro 5	(Wernet et al., 2016)
Distance	10 km	(Eniro, 2017)
Cargo	Max. 200 kg/transport	Leif Johansson
	2 transports/week, 300 000 VR glasses	Leif Johansson
	10 transports/year, 30 000 VR glasses	Calculated by hand, see Appendix II
Number of transports	104 transports/year, 300 000 VR glasses 10.4 transports/year, 30 000 VR glasses	Calculated by hand, see Appendix II
Maintenance transports		
Truck	Diesel truck, Euro 5	(Wernet et al., 2016)

Distance	20 km	(Eniro, 2017)
Number of transports	12 transports/year	Assumption
Storage		
Material	Aluminum	Jotis Nikolis
Weight	193 kg	
Robot IRB 1200		
Materials	Aluminum and iron	Peter Johansson
Weight-% of the materials	60 % of aluminum 40 % of iron	
Weight robot	52 kg	(ABB data sheet, 2014)
Re-fixture		
Material	PC	Johan Bengtsson
Weight	19.10 kg	Jotis Nikolis
Labelling		
Ink	0.714 kg/year, 300 000 VR glasses 0.07 kg/year, 30 000 VR glasses	Lars Ahlqvist
Printer	0.74 kg	Assumption
QR testing		
Scanner	0.74 kg	Assumption
Input to the press		
Material	Steel	Assumption
Weight	30 kg	
Rotation press		
Materials and components	Steel, aluminum, wood and engine	Johan Bengtsson (steel and aluminum) and assumption (wood and engine)
Weight	Steel 154.21 kg Aluminum 90.49 kg Wood 15 kg Engine 20 kg	
ENP transporter		
Materials and components	Steel and engine	Assumption
Weight	Steel 30 kg Engine 5 kg	
Output from the press		
Material	PMMA	Assumption
Weight	15 kg	

Flexlink transporter		
Materials and components	PE, aluminum, engine	David Olsson
Weight	PE 10 kg Aluminum 90 kg Engine 10 kg	Assumption
Scara robot		
Materials	Aluminum and iron	Peter Johansson
Weight-% of the materials	60 % of aluminum 40 % of iron	
Weight	25 kg	(ABB data sheet, 2016)
Eton Systems transporter		
Materials and components	Aluminum, steel, PC and engine	Tomas Nordlund
Weight	Aluminum 75 kg Steel 160 kg PC 10 kg Engine 5 kg	Assumption
Output of lenses		
Material	PMMA	Jotis Nikolis
Weight	4,2 kg	
Assemble station		
Materials and components	Wood, steel and displays	Assumption
Weight and amount	Wood 0.0225 m^3 Steel 27.64 kg Displays 2	Calculated by hand, see Appendix II (wood and steel) and assumption (displays)
Safety cage		
Measures	5000*5000*0.5 mm	Johan Bengtsson
Materials	PC and aluminum	
Weight	PC 16.25 kg Aluminum 36.61 kg	
Ordering station		
Components	Displays	Assumption
Number of displays	6	
Electricity		
Amount	13140 MJ/year, 300 000 VR glasses 5241.6 MJ/year, 30 000 VR-glasses	Adrian Bentland
Type	Swedish average	Assumption

Cameras		
Number of cameras	2	Assumption
Other		
Materials and components	Steel, aluminum and electronics	Johan Bengtsson
Weight	Steel 8466.09 kg Aluminum 15.73 kg Electronics 50 kg	
Sensors		
Weight of sensors	2.88 kg	Johan Bengtsson
Cables		
Total lenght of cables	150 + 1.8 m	Hans Bresäter and Johan Bengtsson respectively
Weight per meter of cable	0.61 kg	(Onninen, 2017)
Weight	92.60 kg	Calculated
Other data used in the calculations		
Density steel	7850 kg/m^3	(Wekla, 2015)
Density aluminium	2712 kg/m^3	(Spectro, 2017)
Density PC	1300 kg/m^3	(Wilson, 2005)
Density PS	1200 kg/m^3	(Berner, 2016)
Density of PUR insulation	12-100 kg/m^3	(Plast- & Kemiföretagen, 2002)

Appendix II - Calculations

Initial screening

Racks

The calculations of the total mass of the racks can be seen below.

The dimensions of one rack was assumed to be 400*300*200 mm. The bottom area and the side walls of the racks could be calculated based on this information, which can be seen below.
Bottom area = 0.4 * 0.3 = 0.12 m^2
Area of two side walls = 0.3 * 0.2 * 2 = 0.12 m^2
Area of two side walls = 0.4 * 0.2 * 2 = 0.16 m^2
Total area = 0.12 + 0.12 + 0.16 = 0.4 m^2

The total volume of the racks could thereafter be calculated when assuming a thickness of 2 mm, which can be seen below.
Total volume = 0.4 * 2 * 10^{-3} = 0.0008 m^3

The total mass of the racks was then calculated, using the density of polystyrene equal to 1.2 g/cm^3, which is visualized below.
Total mass per rack = 0.0008 * 1200 = 0.96 kg ≈ 1 kg

Tables for the assemble station

The calculations of the total mass of the two tables used at the assemble station can be seen below.

The diameter of the steel leg of the table was assumed to be 0.05 m. The height and the thickness of the steel leg were assumed to be 1 m and 3 mm respectively. The calculations of total volume of one steel leg can be seen below.

Volume of a steel leg = (0.0252 * π * 1) – (0.0222 * π * 1) = 0.00044 m^3

The total weight of the 8 steel legs could be calculated using the density of steel equal to 7800 kg/m^3, which can be seen below.
Total weight = 0.00044 * 7800 * 8 = 27.64 kg

The total volume of the wood part of the tables can be seen below.
Total volume = (1 * 1.5 * 0.015) * 2 = 0.045 m^3

Transport from Stora Enso to Universeum

The calculations regarding the transportation from Stora Enso to Universeum can be seen below.

Number of sheets per transport = Number of sheets per pallet * Number of EU Pallets
= 3750 * 4 = 15 000

Cargo per transport = (Number of sheets * Weight of a sheet) + (Number of pallets * Weight of a pallet)

$= (15\ 000 * 90 * 10^{-6}) + (4 * 0.025) = 1.45$ ton/transport

Number of transports per year = Number of VR glasses / Number of sheets per transport
Number of transports (300 000 VR glasses) = 300 000 / 15 000 = 20 transports/year
Number of transports (30 000 VR glasses) = 30 000 / 15 000 = 2 transports/year

Transport from Fristad Plast to Universeum

The calculations regarding the transportation from Fristad Plast to Universeum with 100 racks on one pallet can be seen below.

Cargo per transport = ((Weight of one lens * Number of lenses per rack + Weight of one rack) * Number of racks per transport) + Weight of one EU pallet

$= ((10 * 10^{-6} * 100 + 1 * 10^{-3}) * 100) + 0.025 = 0.225$ ton

Transport from Unvierseum to Fristad Plast

The calculations regarding the transportation from Universeum to Fristad Plast with 100 empty racks on one pallet can be seen below.

Cargo per transport = (Weight of one rack * Number of racks per transport) + Weight of one EU pallet

$= (1 * 10^{-3} * 100) + 0{,}025 = 0.125$ ton

Transport from Universeum to Hans Andersson Recycling

The calculations regarding the transportation from Unviverseum to Hans Andersson Recycling can be seen below.

Produced waste per year = (Weight of a corrugated paper – Weight of a pair of VR glasses) * Number of VR glasses per year
Produced waste per year (300 000 VR glasses) = $(0.09*10^{-3} – 0.03791*10^{-3}) * 300\ 000 =$ 15.63 ton/year
Produced waste per year (30 000 VR glasses) = $(0.090*10^{-3}-0.03791*10^{-3}) * 30\ 000 = 1.56$ ton/year

It was given that there will be two transports per week which means 104 transports per year for the case with 300 000 VR glasses.
Cargo per transport = Produced waste / Number of transports
Cargo weight per transport (300 000 VR glasses) = 15.63 / 104 = 0.15 ton/transport

In this case, it was not known the number of transports per year for the case with 30 000 VR glasses but the cargo was assumed to be the same as for the case with 300 000 VR glasses.
Number of transports (30 000 VR glasses) = Produced waste / Cargo per transport
Number of transports (30 000 VR glasses) = 1.56 / 0.15 = 10.4

Transport from Stora Enso to IL recycling

The calculations regarding the transportation Stora Enso to IL recycling can be seen below.

The amount of produced waste at the production at Stora Enso was equal to 5 % of the total weight of the corrugated paper.

Produced waste per year = 5 % * Weight of a sheet * Number of sheets per year
Produced waste per year (300 000 VR glasses) = 0.05 * 0.09 * 300 000 = 1350 kg/year
Produced waste per year (30 000 VR glasses) = 0.05 * 0.09 * 30 000 = 135 kg/year

Number of transports per year = Produced waste per year / Cargo
Total amount of transports (300 000 VR glasses) = 1350 / 150 = 9 transports/year
Total amount of transports (30 000 VR glasses) = 135 / 150 = 0.9 ≈ 1 transport/year

Detailed assessment

Alternative dimensions

Lenses

When calculating the weight for the lenses in the two different scenarios, the first was to calculate the weight of 1 mm^2 which is shown below.

Weight of 1 mm^2 = Weight of one lens / Total area of one lens
= 10 / (12.52 * π * 2 + (5 * 20)) = 0.0092 g

The calculation of the weight of the lenses in Scenario 1 (diameter of 25 mm) is shown below.

Weight of lens = Weight of 1 mm^2 * Total area of the lenses
= 0.0092 * 981.75 = 9.07 ≈ 9 g

The calculation of the weight of the lenses in Scenario 2 (diameter of 34 mm) is shown below.

Weight of lens = Weight of 1 mm^2 * Total area of the lenses
= 0.0092 * 1815.84 = 16.79 ≈ 17 g

The calculations of the weight of the corrugated board box (assumed measures are 60*30*10 mm) are shown below.

Weight of 1 mm^2 = Weight of one sheet / Total area of one sheet
= 90 / (400*600) = 0.000375 g

Weight of corrugated board box = Weight of 1 mm^2 * Total area of one box
= 0.000375 * 3600 = 1.35 ≈ 1.4 g

Racks

The calculations of the total mass of the racks for the 3 different scenarios can be seen below.

Scenario 1 (600*400*200 mm)
Bottom area = 0.6 * 0.4 = 0.24 m^2
Area of two side walls = 0.6 * 0.2 * 2 = 0.36 m^2
Area of two side walls = 0.4 * 0.2 * 2 = 0.16 m^2
Total area = 0.24 + 0.36 + 0.16 = 0.76 m^2

The total volume of the racks could thereafter be calculated when assuming a thickness of 2 mm, which can be seen below.

Total volume = 0.76 * 2 * 10^{-3} = 0.00152 m^3

The total mass of the racks was then calculated, using the density of polystyrene equal to 1.2 g/cm^3, which is visualized below.
Total mass / rack = 0.00152 * 1200 = 1.824 kg ≈ 1.8 kg

Scenario 2 (600*800*200)
Bottom area = 0.6 * 0.8 = 0.48 m^2
Area of two side walls = 0.8 * 0.2 * 2 = 0.32 m^2
Area of two side walls = 0.6 * 0.2 * 2 = 0.24 m^2
Total area = 0.48 + 0.32 + 0.24 = 1.04 m^2

The total volume of the racks could thereafter be calculated when assuming a thickness of 2 mm, which can be seen below.
Total volume = 1.04 * 2 * 10^{-3} = 0.00208 m^3

The total mass of the racks was then calculated, using the density of polystyrene equal to 1.2 g/cm^3, which is visualized below.
Total mass per rack = 0.00208 * 1200 = 2.496 kg ≈ 2.5 kg

Scenario 3 (300*400*200 mm)
Bottom area = 0.4 * 0.3 = 0.12 m^2
Area of two side walls = 0.3 * 0.2 * 2 = 0.12 m^2
Area of two side walls = 0.4 * 0.2 * 2 = 0.16 m^2
Total area = 0.12 + 0.12 + 0.16 = 0.4 m^2

The total volume of the racks could thereafter be calculated when assuming a thickness of 2 mm, which can be seen below.
Total volume = 0.4 * 1 * 10^{-3} = 0.0004 m^3

The total mass of the racks was then calculated, using the density of polystyrene equal to 1.2 g/cm^3, which is visualized below.
Total mass / rack = 0.0004 * 1200 = 0.48 kg ≈ 0.5 kg

Corrugated paper
The calculations of the total weight of a corrugated paper sheet with the new dimensions (600*350 mm) can be seen below.
Weight of 1 mm^2 = Weight of one sheet / Area of one sheet
= 90 / (600 * 400) = 0.000375 g
Weight with new dimensions = Weight of 1 mm^2 * Area of sheet with new dimensions
= 0.000375 * (600 * 350) = 78.75 g

Alternative layouts of the lens line

Scenario 3
The calculations made for the vending machine (1500*600*1000 mm) are shown below.
Total surface area of steel = (2 * surface area of the top) + (2 * surface area of sidewall) + surface area of back wall)
= (2 * 0.6 * 1.0) + (2 * 1.5 * 1.0) + (1.5 * 0.6) = 5.1 m^2 ≈ 5 m^2
Volume of steel = Thickness of steel * Total surface area of steel
= (1.291 * 10^{-3}) * 5 = 0.006455 m^3
Weight of steel = Volume of steel * density of steel
= 0.006455 * 7850 = 50.67 kg ≈ 50 kg

Total surface area of PC = surface area of front wall
$= (0.6 * 1.5) = 0.9\ m^2 \approx 1\ m^2$
Volume of PC = Thickness of PC * Total surface area of PC
$= 0.005 * 1 = 0.005\ m^3$
Weight of PC = Volume of PC * density of PC
= 0.005 * 1300 = 6.5 kg

Total surface area of polyurethane insulation = Total surface area of steel
$= 5\ m^2$
Volume of polyurethane insulation = Thickness of polyurethane insulation * Total surface area of polyurethane insulation
$= 0.005 * 5 = 0.025\ m^3$
Weight of PC = Volume of PC * density of PC
= 0.005 * 50 = 1.25 kg ≈ 1.3 kg

The calculations of the weight of a corrugated board box (assumed measures are 100*30*10 mm) that the lenses are stored in is shown below.
Weight of 1 mm^2 = Weight of one sheet / Total area of one sheet
= 90 / (400*600) = 0.000375 g
Weight of a corrugated board box = Weight of 1 mm^2 * Total area of one box
= 0.000375 * 8600 = 3.23 ≈ 3.2 g

Appendix III – Results initial screening

300 000 VR glasses

Figure A1-A11 illustrates the environmental impact for all parts of the life cycle of 300 000 VR glasses.

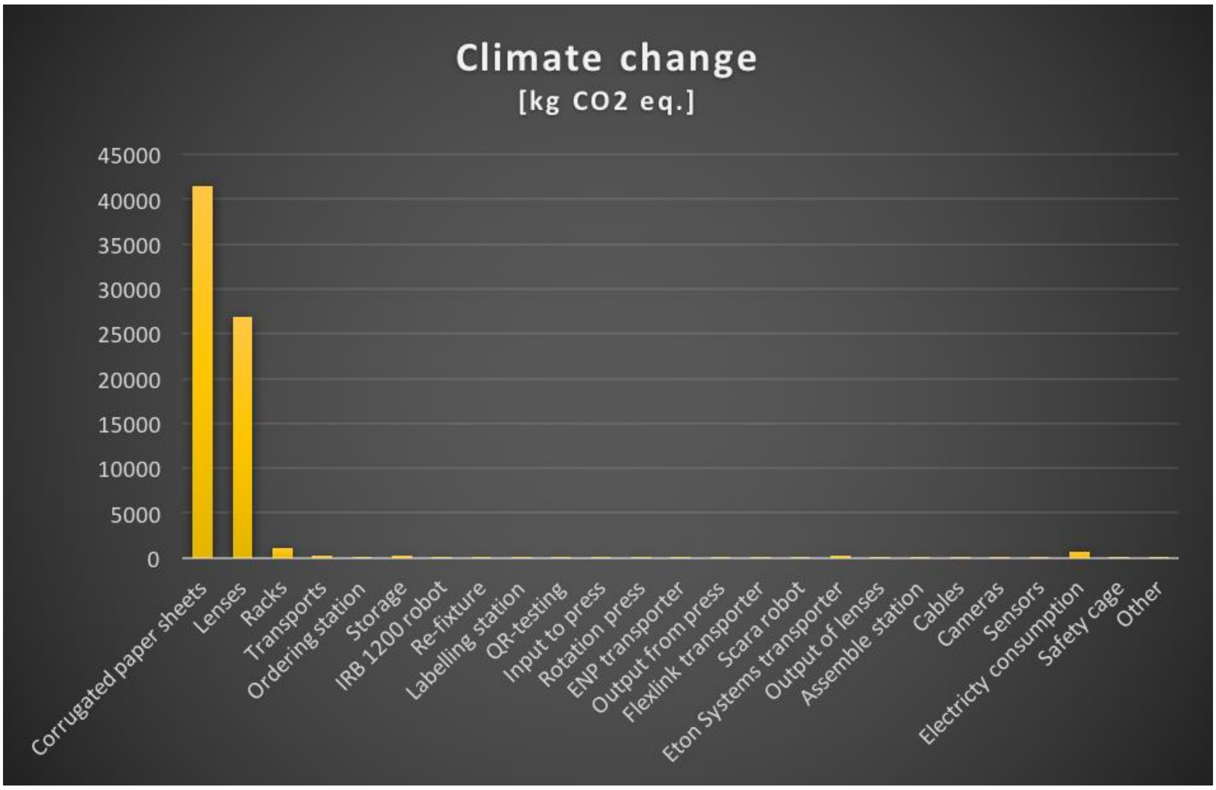

Figure A1. *An illustration of the contribution to the climate change for all parts of the life cycle.*

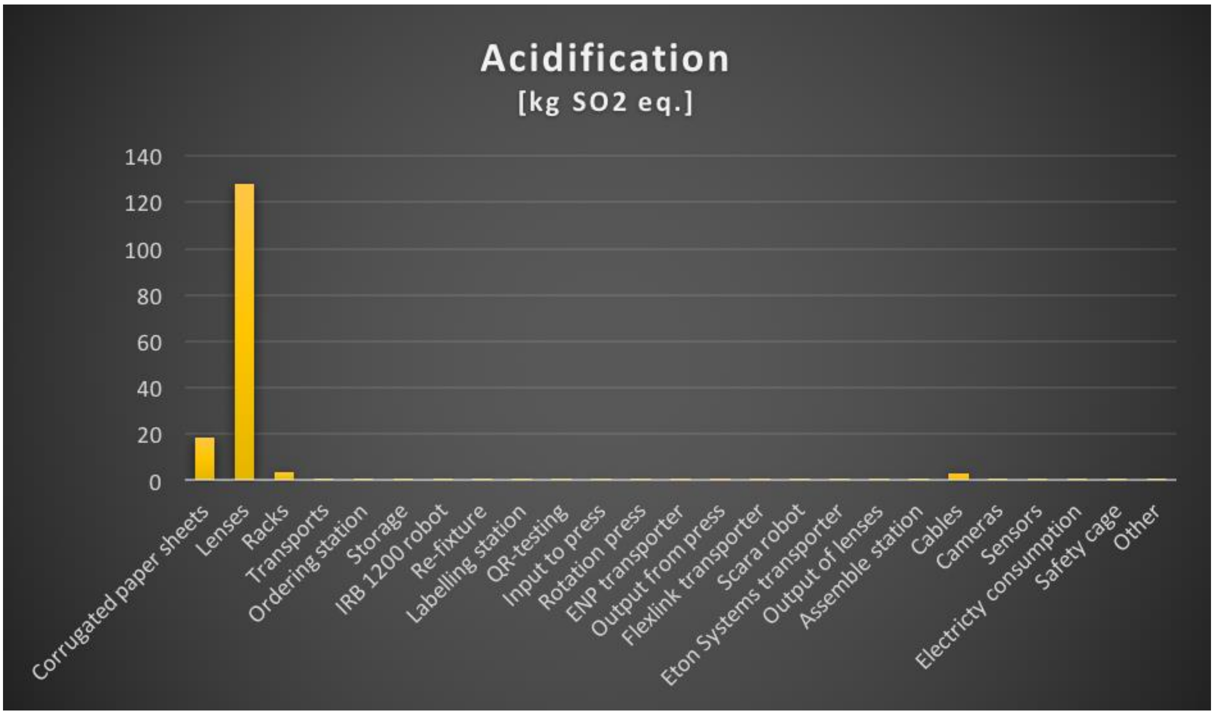

Figure A2. *An illustration of the contribution to the acidification for all parts of the life cycle.*

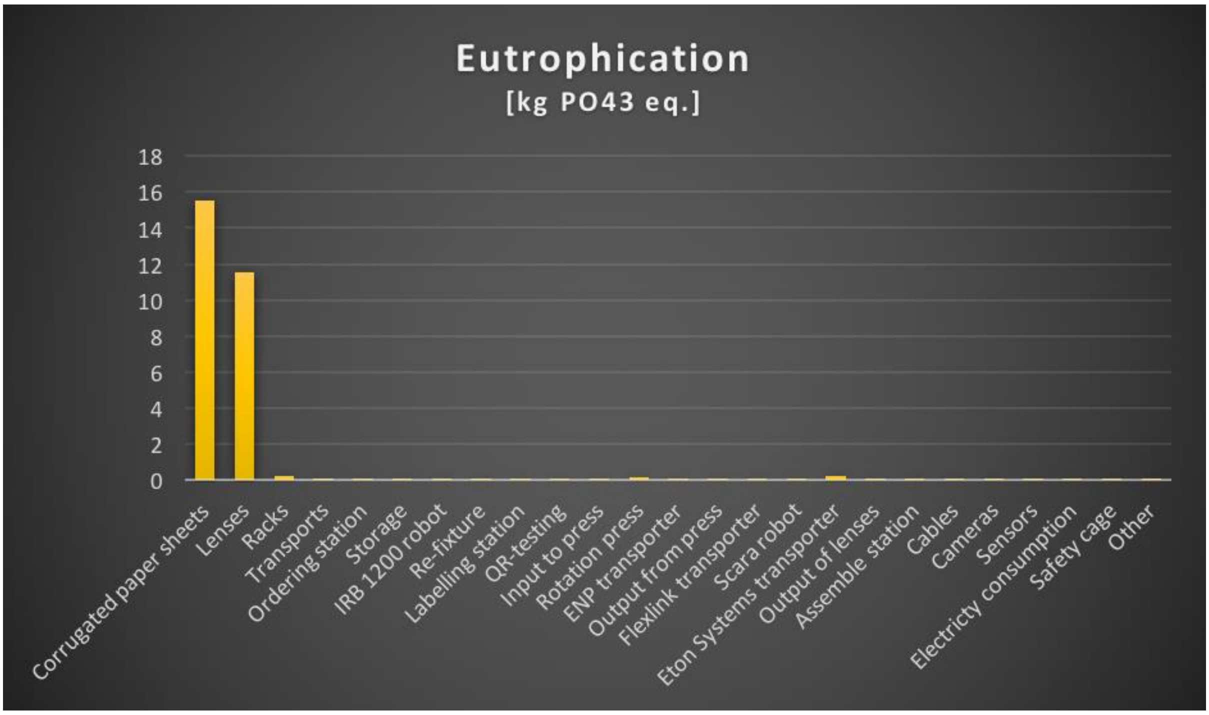

Figure A3. *An illustration of the contribution to the eutrophication for all parts of the life cycle.*

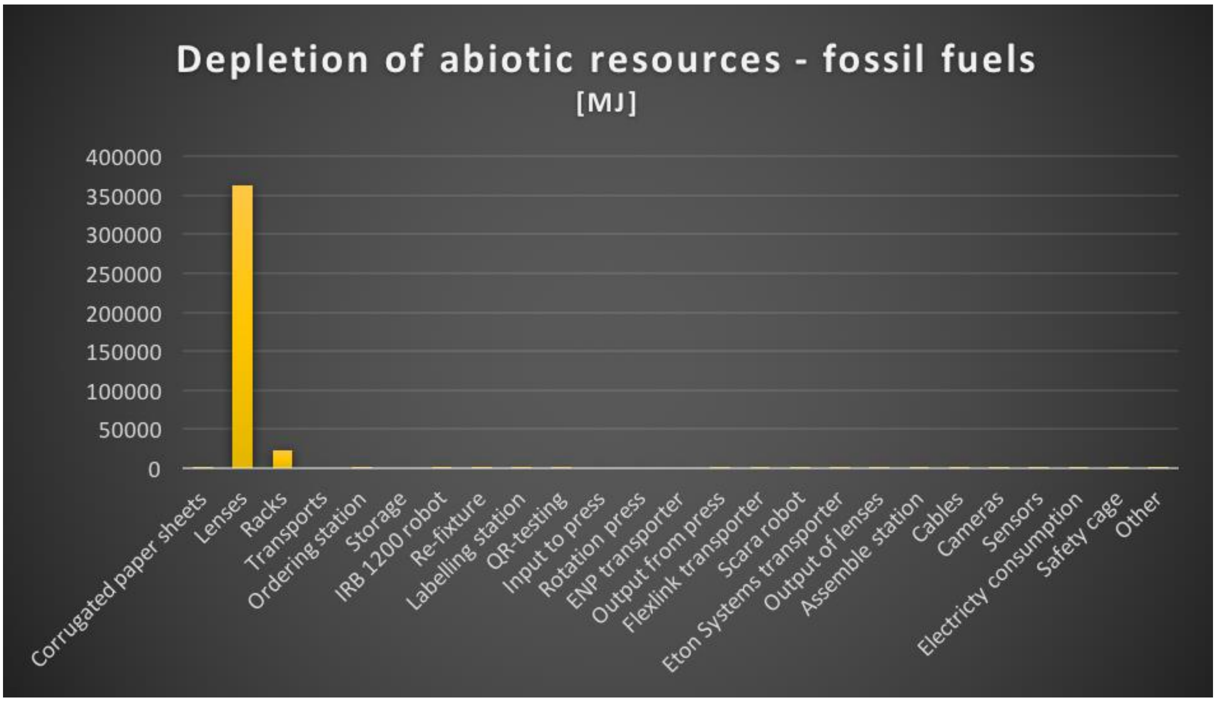

Figure A4. *An illustration of the contribution to the depletion of abiotic resources - fossil fuels for all parts of the life cycle.*

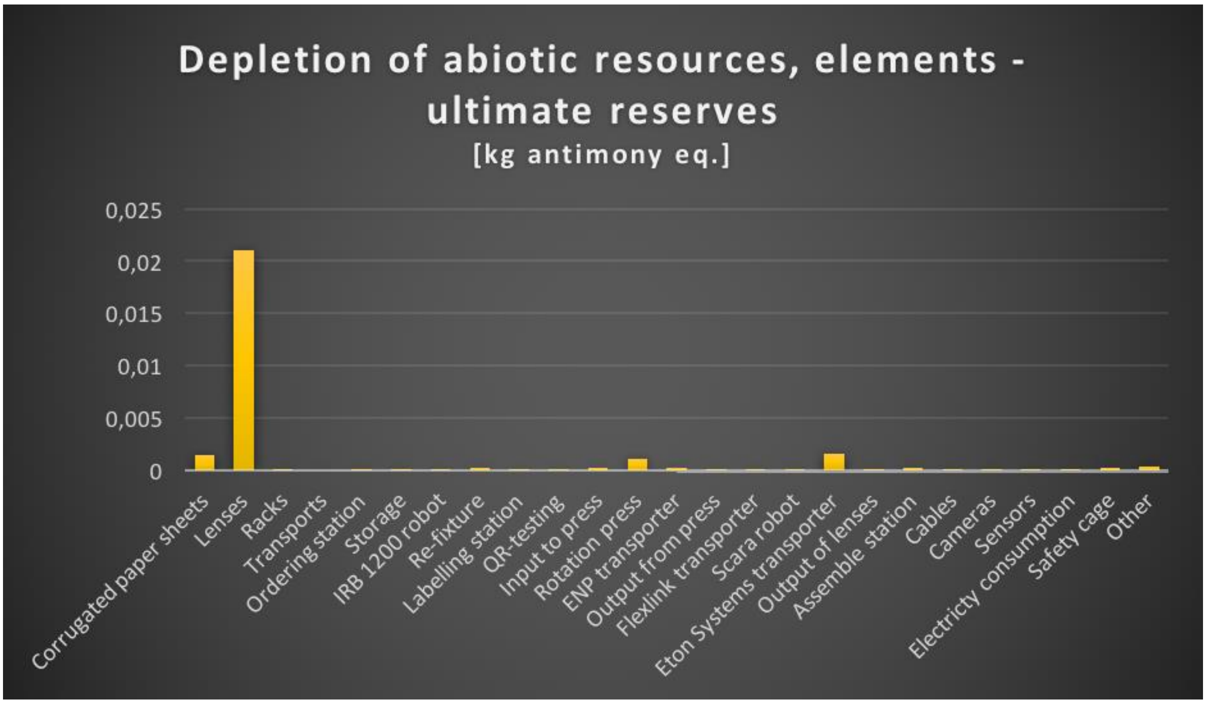

Figure A5. *An illustration of the contribution to the depletion of abiotic resources - ultimate reserves for all parts of the life cycle.*

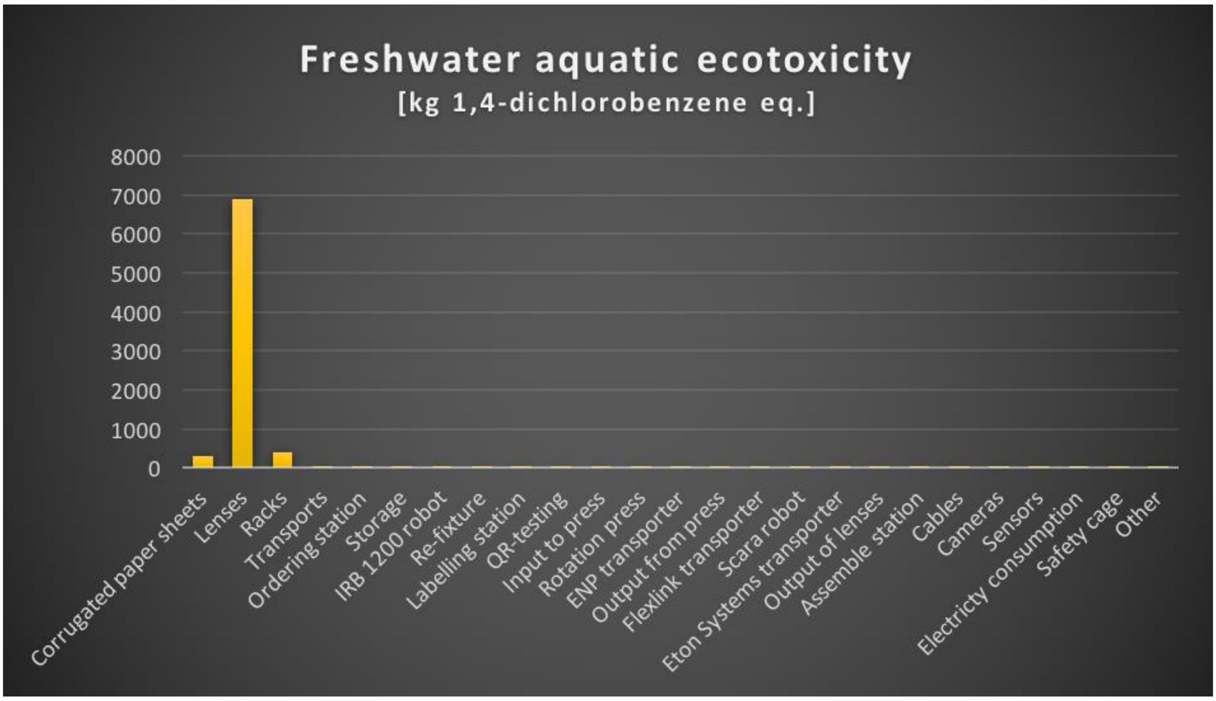

Figure A6. *An illustration of the contribution to the freshwater aquatic ecotoxicity for all parts of the life cycle.*

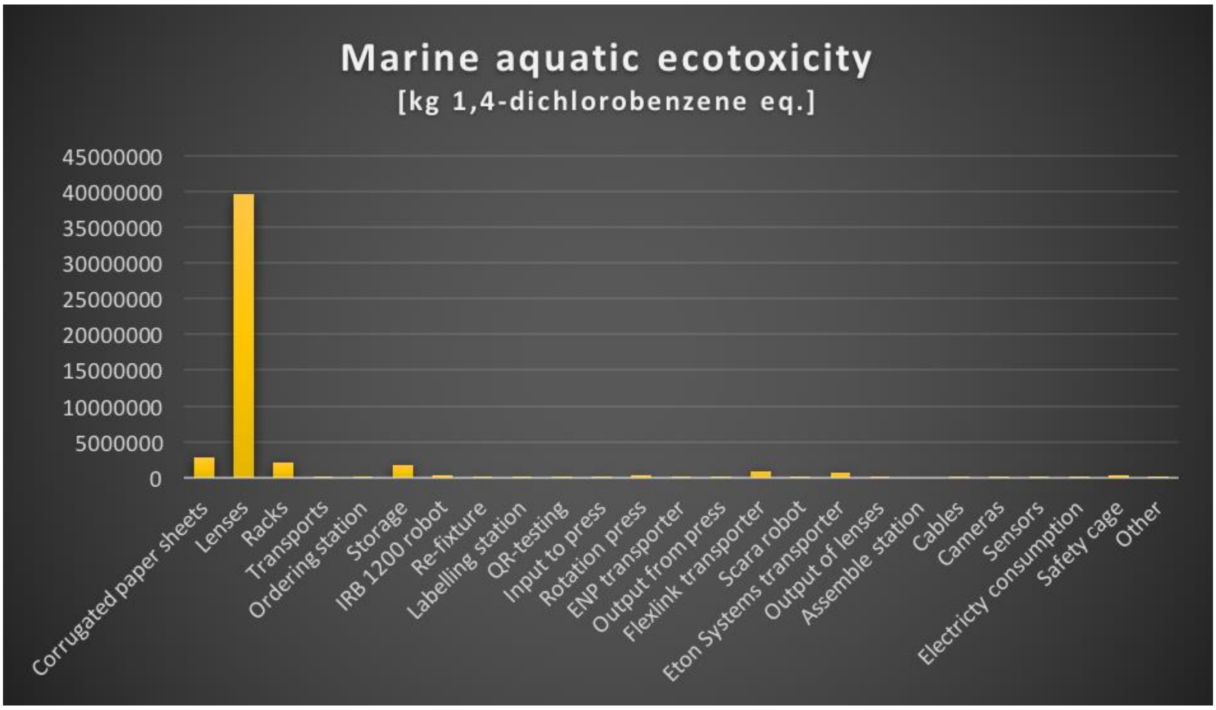

Figure A7. *An illustration of the contribution to the marine aquatic ecotoxicity for all parts of the life cycle.*

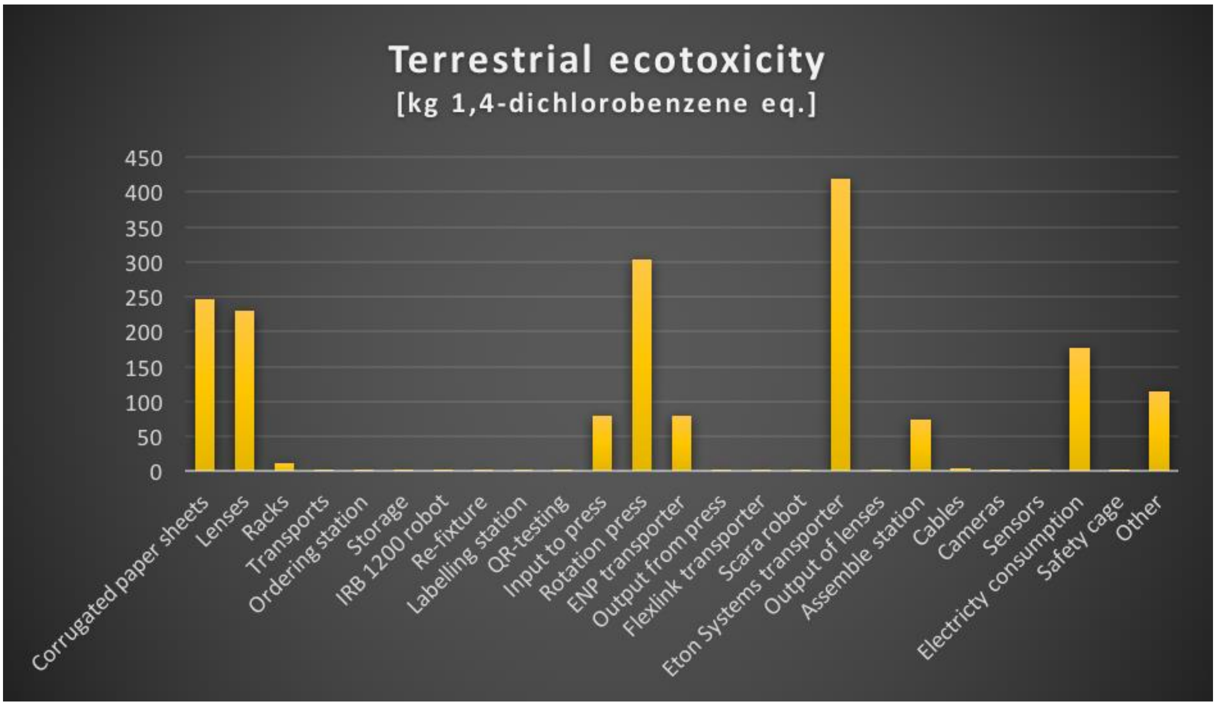

Figure A8. *An illustration of the contribution to the terrestrial ecotoxicity for all parts of the life cycle.*

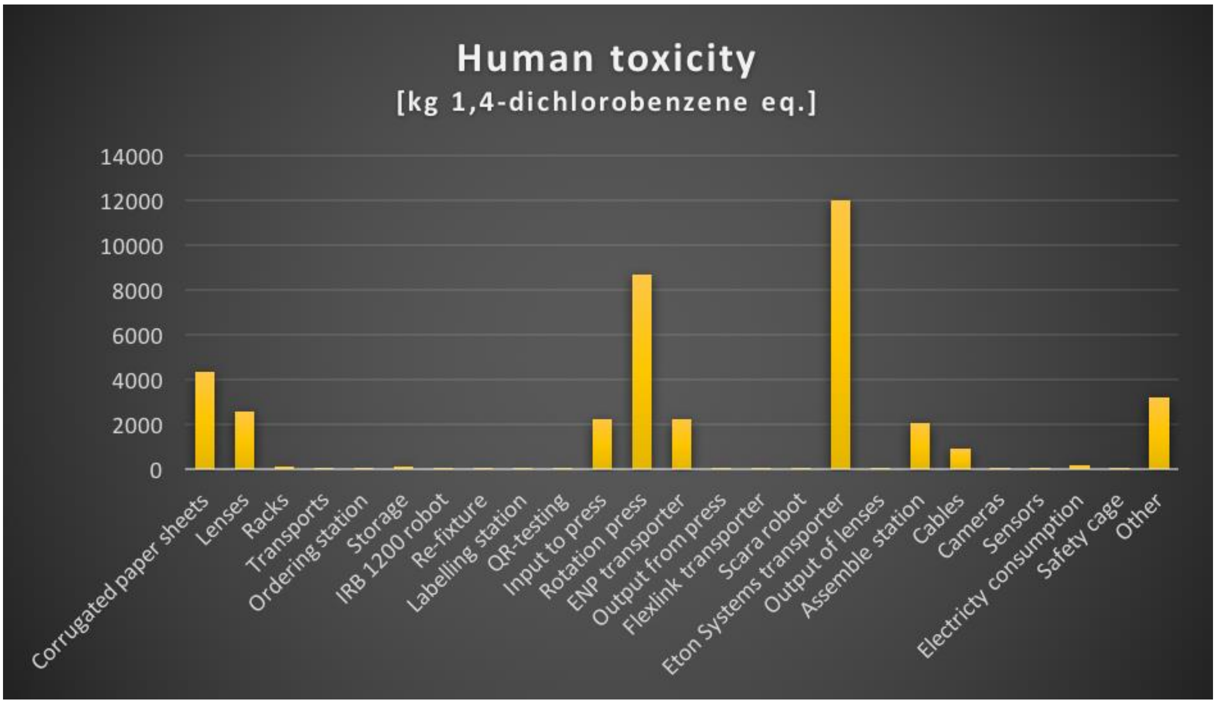

Figure A9. *An illustration of the contribution to the human toxicity for all parts of the life cycle.*

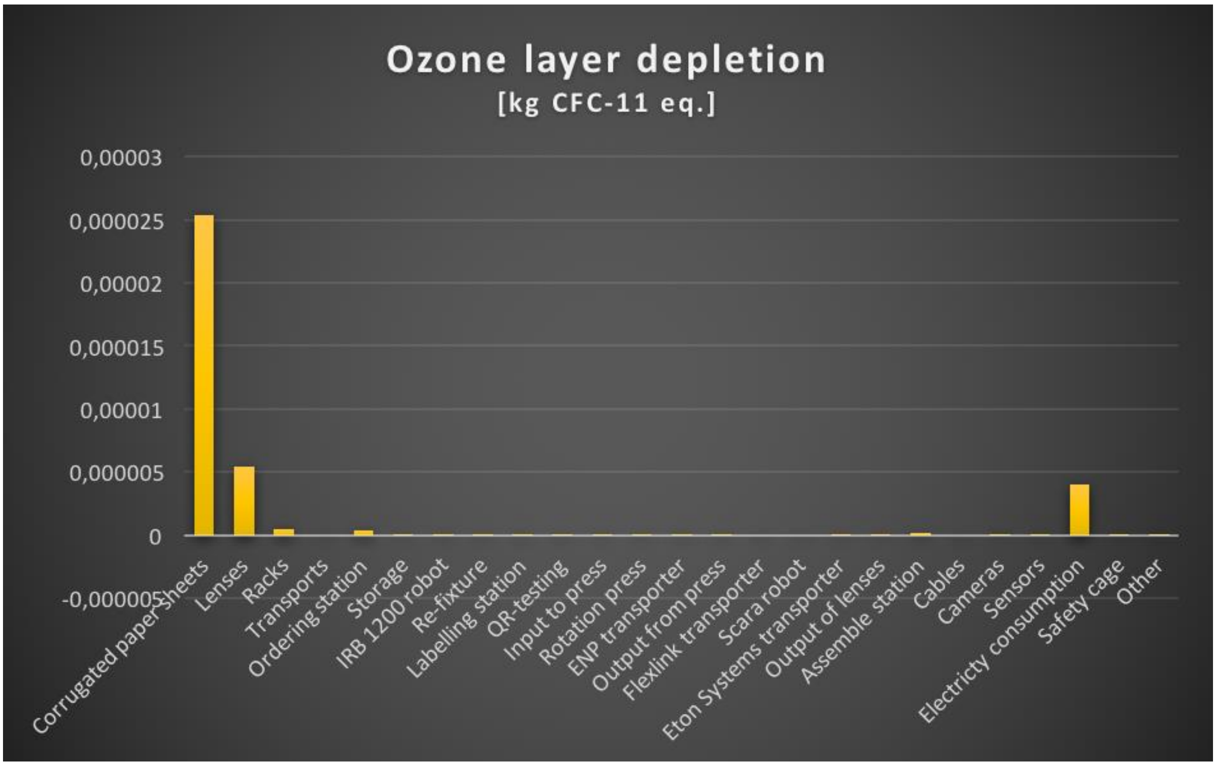

Figure A10. *An illustration of the contribution to the ozone layer depletion for all parts of the life cycle.*

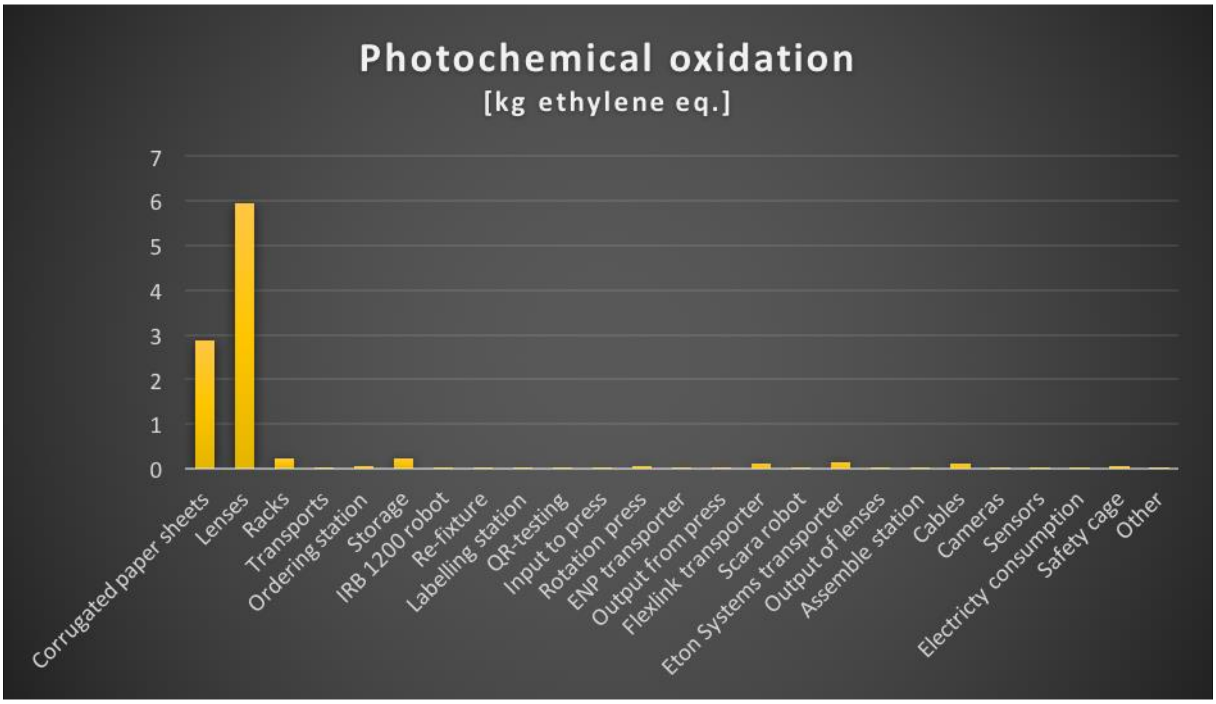

Figure A11. *An illustration of the contribution to the photochemical oxidation for all parts of the life cycle.*

30 00 VR glasses

Figure A12-A22 illustrates the environmental impact for all parts of the life cycle of 30 000 VR glasses.

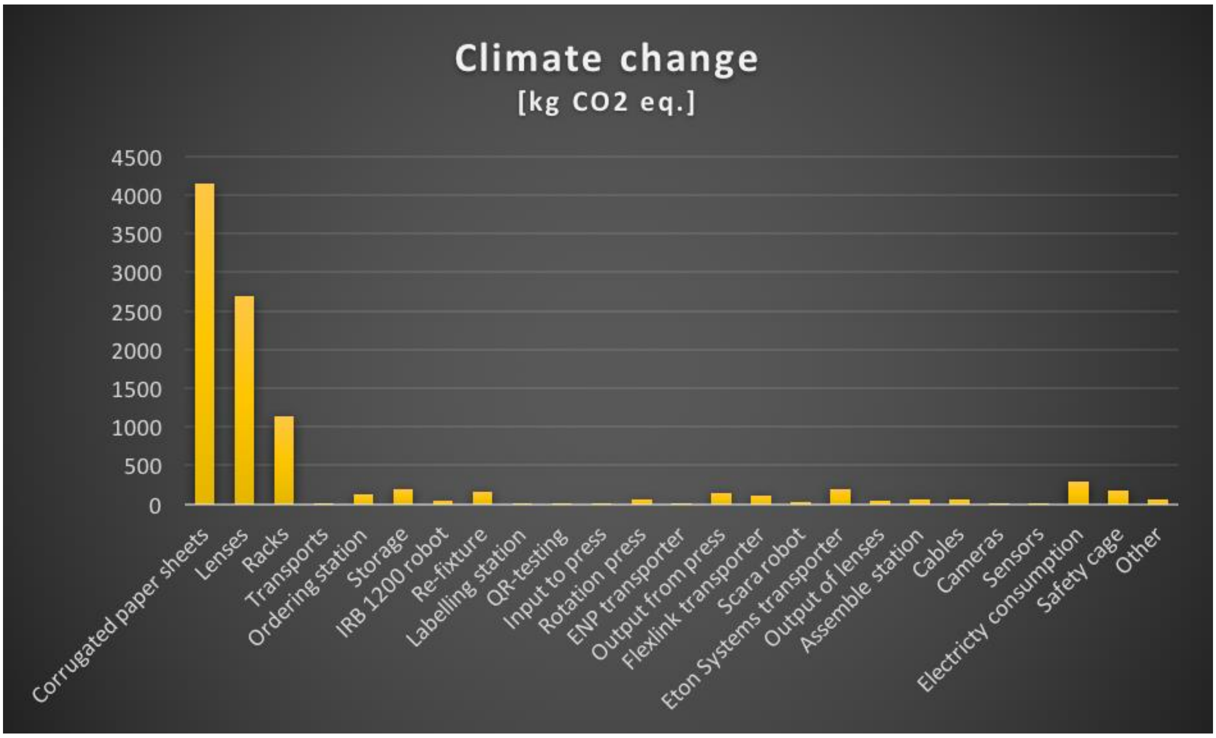

Figure A12. *An illustration of the contribution to the climate change for all parts of the life cycle.*

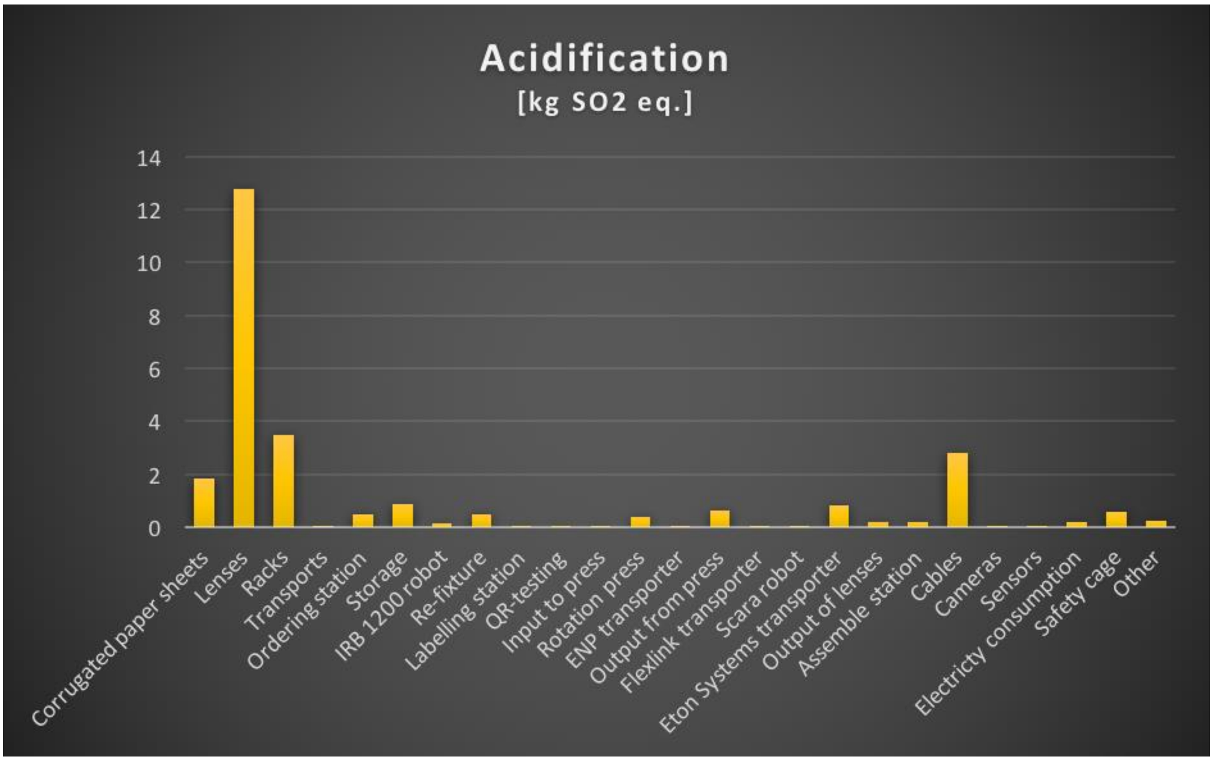

Figure A13. *An illustration of the contribution to the acidification for all parts of the life cycle.*

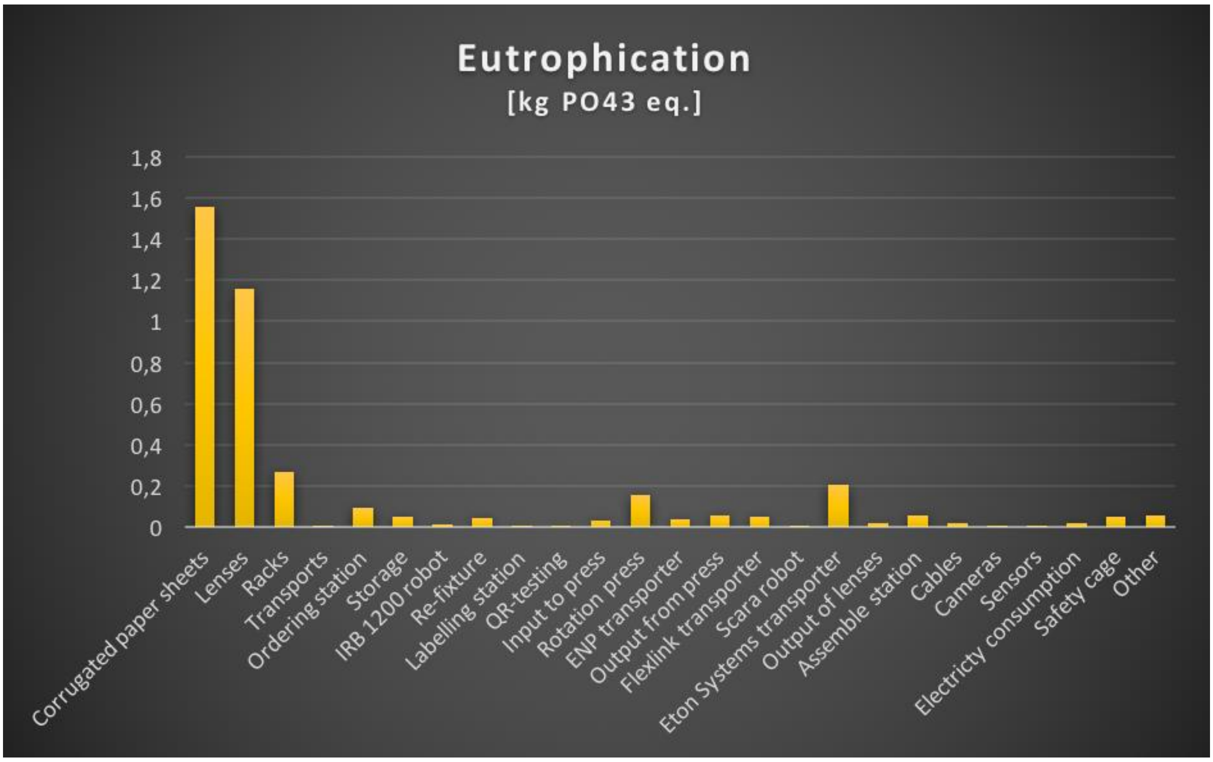

Figure A14. *An illustration of the contribution to the eutrophication for all parts of the life cycle.*

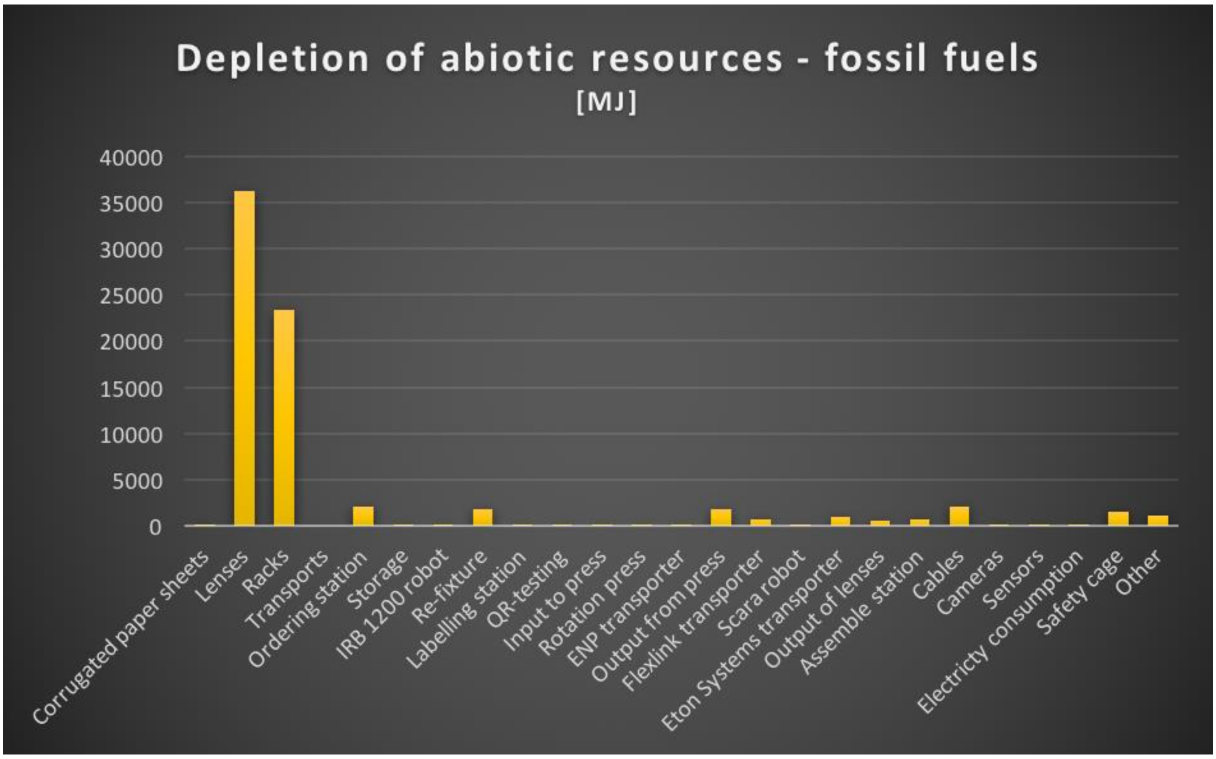

Figure A15. *An illustration of the contribution to the depletion of abiotic resources - fossil fuels for all parts of the life cycle.*

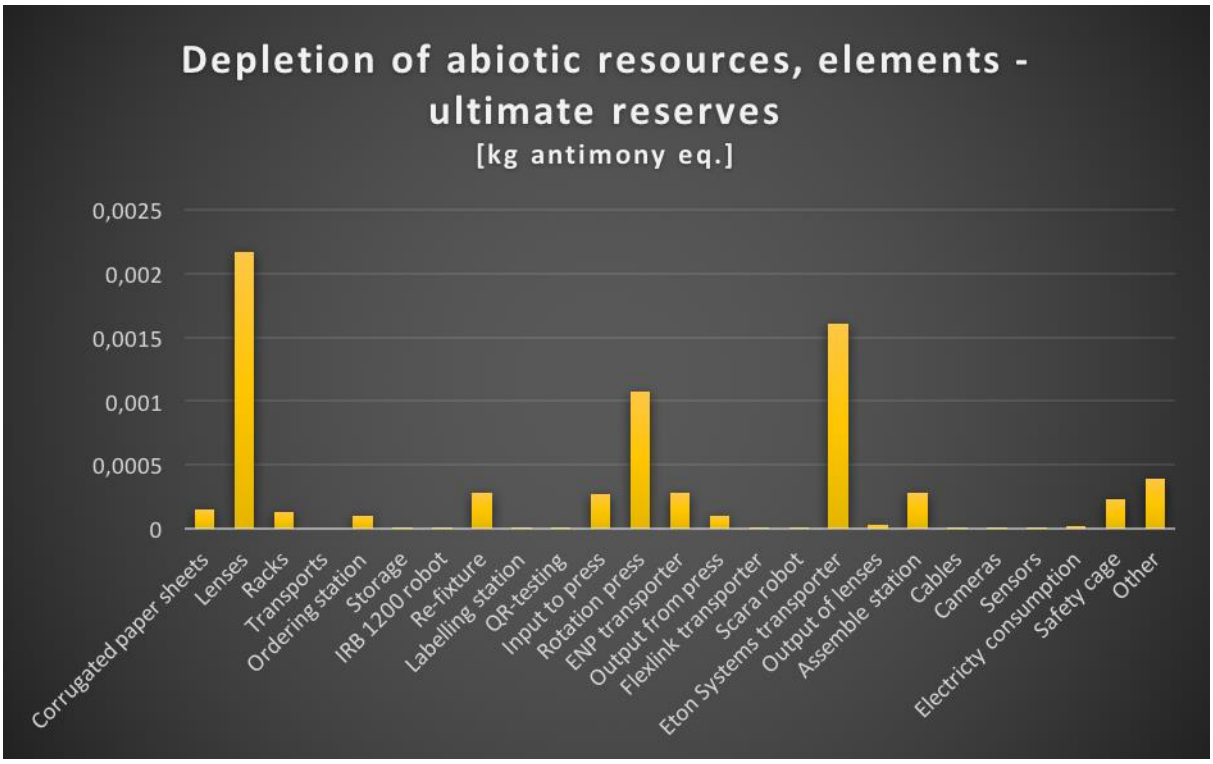

Figure A16. *An illustration of the contribution to the depletion of abiotic resources - ultimate reserves for all parts of the life cycle.*

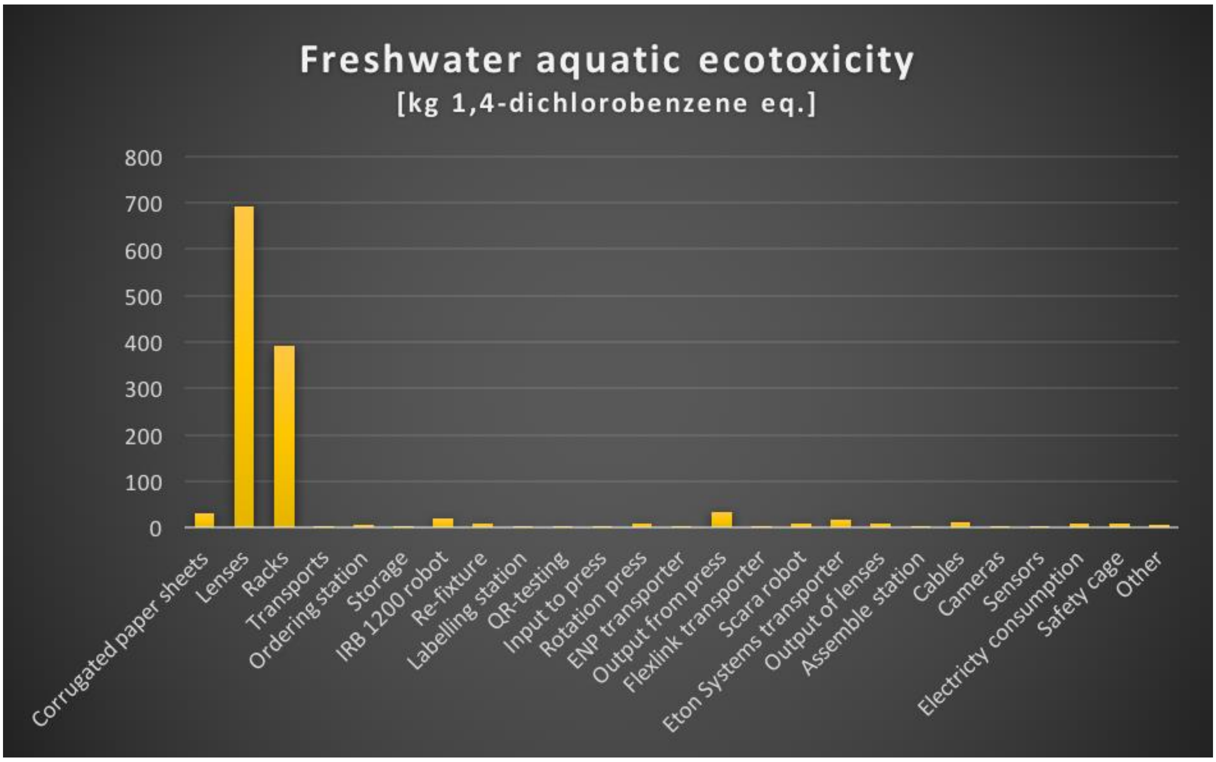

Figure A17. *An illustration of the contribution to the freshwater aquatic ecotoxicity for all parts of the life cycle.*

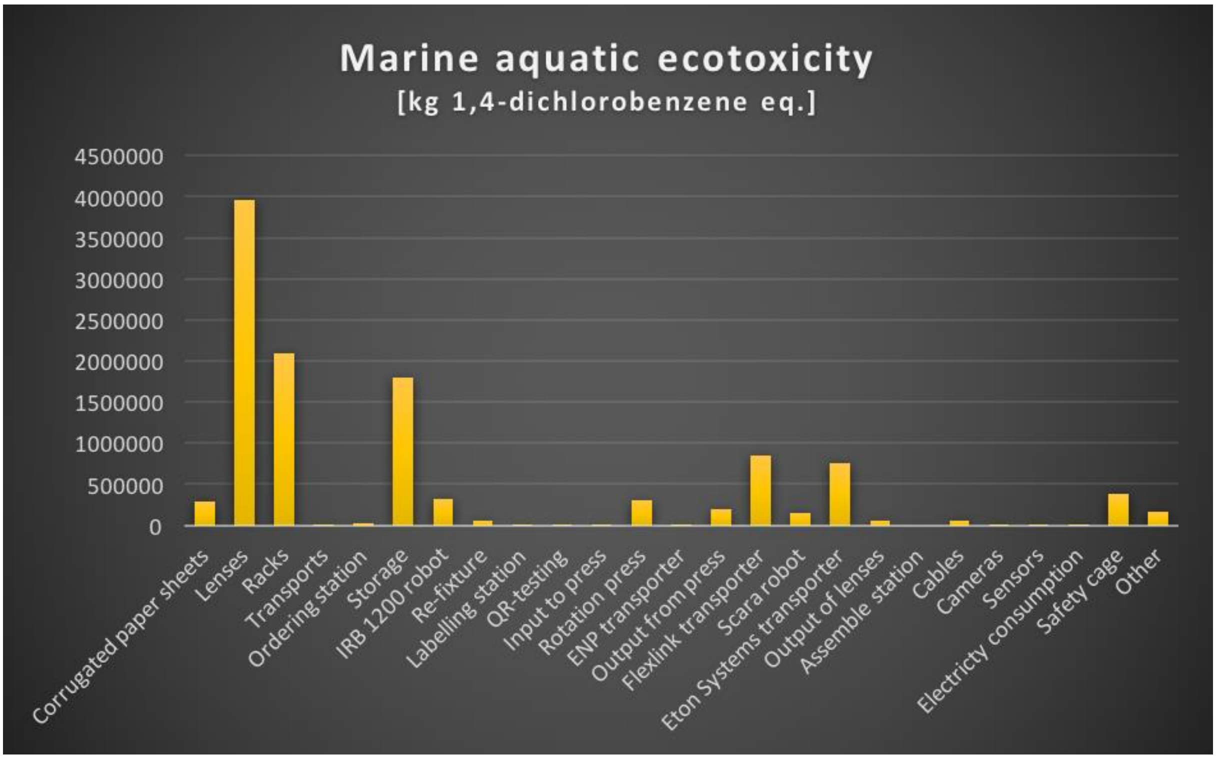

Figure A18. *An illustration of the contribution to the marine aquatic ecotoxicity for all parts of the life cycle.*

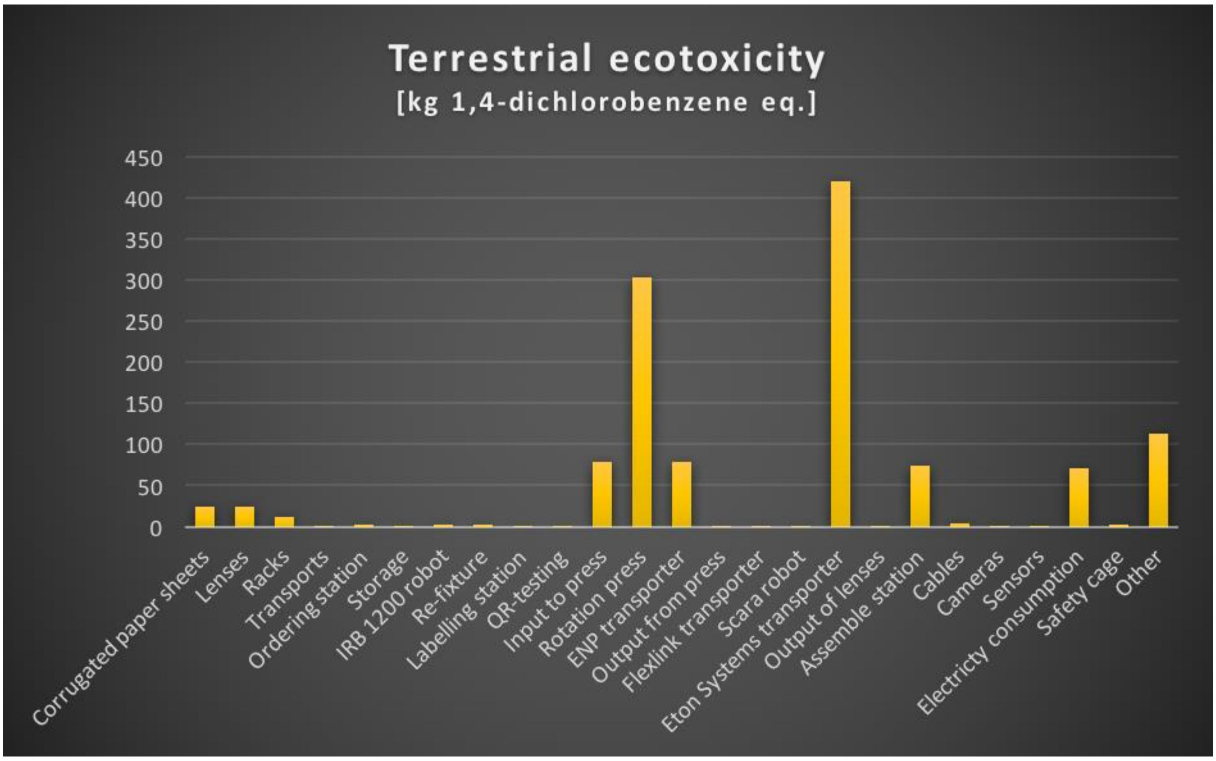

Figure A19. *An illustration of the contribution to the terrestrial ecotoxicity for all parts of the life cycle.*

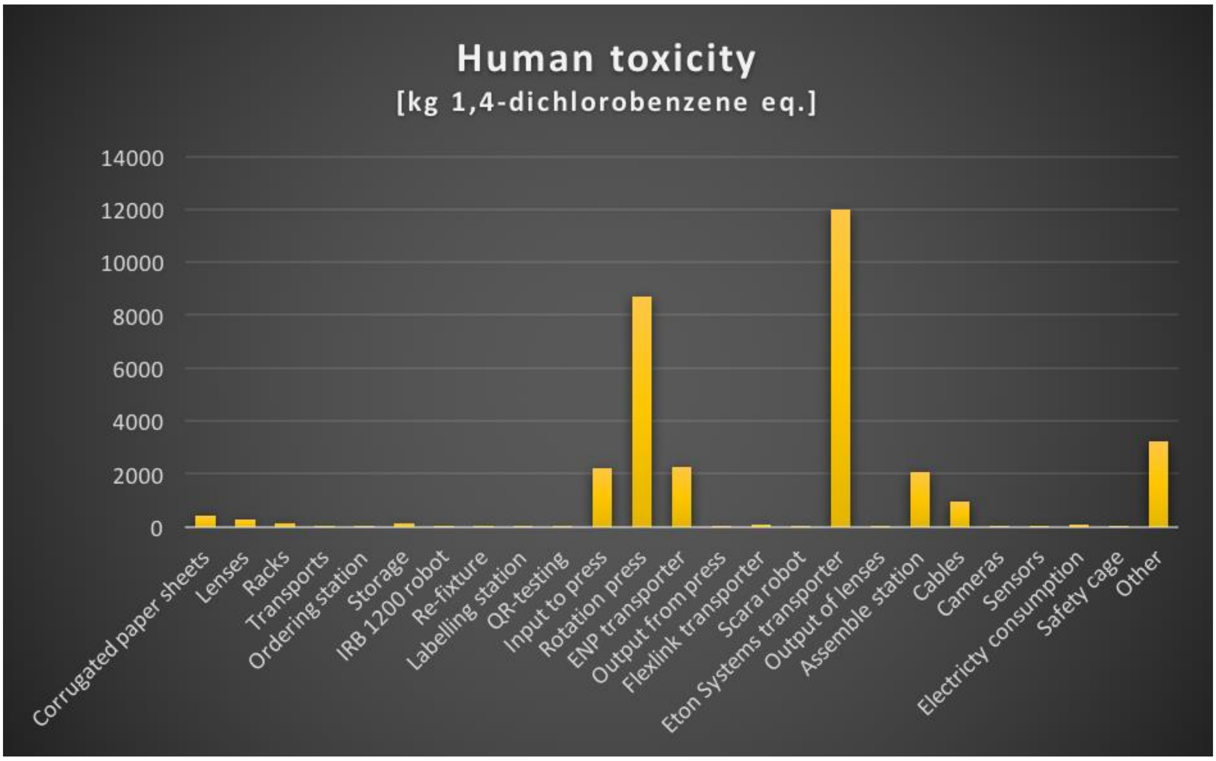

Figure A20. *An illustration of the contribution to the human toxicity for all parts of the life cycle.*

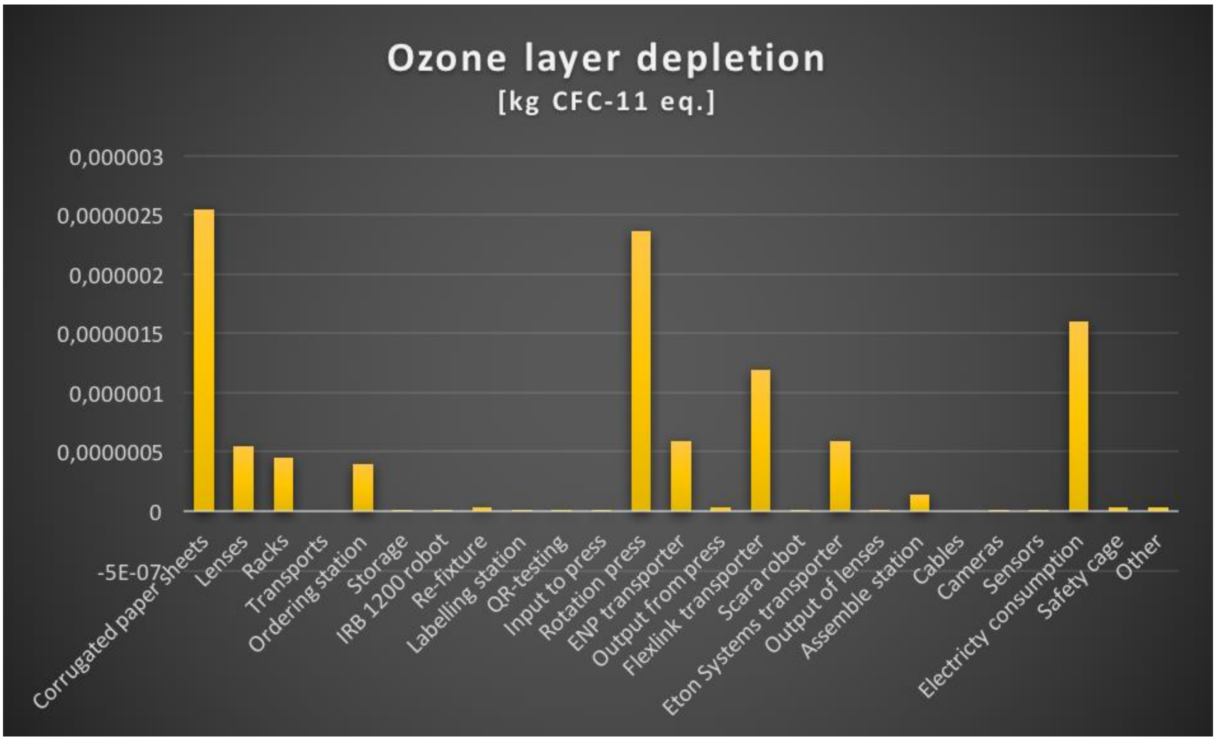

Figure A21. *An illustration of the contribution to the ozone layer depletion for all parts of the life cycle.*

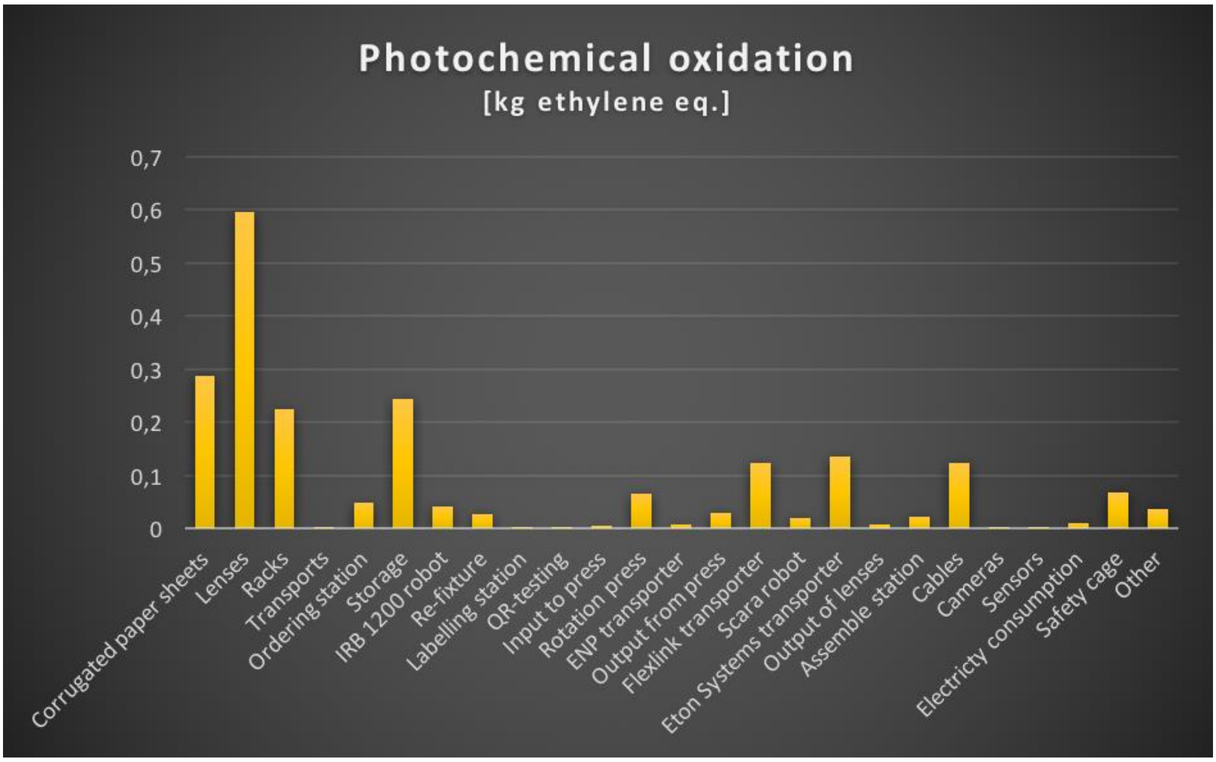

Figure A22. *An illustration of the contribution to the photochemical oxidation for all parts of the life cycle.*

Appendix IV – Reports from the literature review

All 29 reports read in the literature review of sustainable digitalization are presented below together with the sustainability dimension(s) highlighted in the report.

- Den högre utbildningens roll i en digital tid *[The role of higher education in a digital era]* (Gulliksen, 2016)
    - Economic
    - Social

- Det datadrivna samhället *[The data driven society]* (Bylund et al., 2016)
    - Economic
    - Social

- Det sociala kontraktet i digital tid *[The social contract in a digital era]* (Ekholm et al., 2016)
    - Economic
    - Social

- Digitalisering av svensk industri – kartläggning av svenska styrkor och utmaningar *[Digitalization of the Swedish industry - a mapping of the Swedish strengths and challenges]* (Bossen et al., 2016)
    - Economic

- Digitaliseringens betydelse för industrins förnyelse – En rapport från Teknikföretagen. *[The importance of digitalization for the innovation of the industry- A report from the technology companies]* (Teknikföretagen, 2015)
    - Economic (mainly)
    - Social (to some extent)
    - Environment (to some extent)

- Digitaliseringens dynamik – en ESO-rapport om strukturomvandlingen i svenskt näringsliv *[The dynamics of digitalization - An ESO-report about the structural transformation in the industrial life of Sweden]* (Heyman et al., 2016)
    - Economic
    - Social

- Digitalisering för ett hållbart klimat *[Digitalization for a sustainable climate]* (Gustafsson et al., 2016)
    - Environment

- Digitalization in industrial products – Harnessing the power of digital (EY, 2016)
    - Economic

- Digitalisering och hållbar konsumtion *[Digitalization and sustainable consumption]* (Höjer et al., 2015)

- Environment

- Digitalisering och konsumentintresset *[Digitalization and the interest of consumers]* (Konsumentverket, 2016)
  - Economic
  - Social

- Digitaliseringens transformerande kraft – vägval för framtiden *[The transforming force of digitalization - a choice of path for the future]* (Digitaliseringskommissionen, 2015a)
  - Economic
  - Social

- En digital agenda i människans tjänst – Sveriges digitala ekosystem, dess aktörer och drivkrafter *[A digital agenda in the favor of humans - Sweden's digital ecosystem, its actors and driving forces]* (Digitaliseringskommissionen, 2013)
  - Economic
  - Social

- Effects of digitalization on the service sector and employment (European Economic and Social Committee, 2015)
  - Economic
  - Social

- Future Smart Industry – Perspektiv på industriomvandling *[Future Smart Industry - Perspective on the transformation of the industry]* (Larsson, 2015)
  - Economic (mainly)
  - Social (to some extent)
  - Environment (to some extent)

- Gör Sverige i framtiden – digital kompetens *[Make Sweden in the future - digital competence]* (Digitaliseringskommissionen, 2015b)
  - Economic
  - Social

- Hur hänger hållbarhet och digitalisering samman? *[How is sustainability and digitalization connected?]* (BiTA, 2016)
  - Economic
  - Social
  - Environment

- ICT for Sustainability: An emerging Research Field (Hilty et al., 2014)
  - Environment (mainly)
  - Economic (to some extent)
  - Social (to some extent)

- ICT Innovations for Sustainability (Hilty et al., 2015)
  - Economic (mainly)
  - Environment (to some extent)

- Industry 4.0. How digitization makes the supply chain more efficient, agile, and customer-focused (Schrauf et al., 2016)
    - Economic

- Industry 4.0. How to navigate digitization of the manufacturing sector (McKinsey & Company, 2015)
    - Economic

- Information Technology and Sustainability – Essays on the Relationship between ICT and Sustainable Development (Chapter 1 and 2) (Hilty, 2008)
    - Economic
    - Social
    - Environment

- Integrating digital economy and green economy: opportunities for sustainable development (Ciocoiu, 2011)
    - Economic

- Kartlegging av hindre for digitale forretningsprosesser *[A mapping of the obstacles for digital business processes]* (KPMG, 2014)
    - Economic

- Smart Industri – en nyindustrialiseringsstrategi för Sverige *[Smart industry - a new strategy for industrialization in Sweden]* (Regeringskansliet, 2015)
    - Economic
    - Social
    - Environment

- Sustainability and ICT – An overview of the field (Hilty et al., 2011)
    - Economic
    - Environment

- Svenska företags syn på sin digitalisering *[Swedish companies view on their digitalization]* (Roland Berger, 2016)
    - Economic

- The Fourth Wave of Digitalization and Public Transport: Opportunities and Challenges (Davidsson et al., 2016)
    - Economic
    - Social
    - Environment

- The game-changing potential of digitalization for sustainability: possibilities, perils, and pathways (Seele et al., 2017)
    - Economic
    - Social
    - Environment

- The relevance of information and communication technologies for environmental sustainability – a prospective simulation study (Hilty et al., 2006)

- Environment