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Life cycle assessment on a passenger’s airbag at Volvo cars

Master’s thesis in Industrial Ecology

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SUMMARY

Environmental concerns have received considerable attention in recent decades, and there is a greater understanding of how human activities affect and degrade the environment.
In recent decades, transportation systems have been one of the major contributors to poor air quality, noise, and climate change. It is also well known that the automotive sector confronts major environmental challenges not only for fuel consumption in terms of emissions during usage but also during manufacturing processes.
Due to the importance of both safety and sustainability standards, Volvo Cars is concerned about reducing the environmental impact of its products. A life cycle assessment (LCA) can help them gain a better understanding of the environmental performance of some of their products.
The aim of the study was to analyse, assess and provide relevant information regarding the environmental performance of a car airbag during its manufacturing process, with this objective, an LCA has been performed from cradle to gate for each of the ingoing parts of a passenger airbag.
The study demonstrated that the bag, inflator and housing of the airbag were the components that contributed most to the environmental impact. The selected impact categories were climate impact, depletion of abiotic resources and freshwater consumption. More specifically, the production and use of plastics such polyamide-6,6 (PA-6,6) and polypropylene, and other materials such as steel and glass fibre production contributed significantly.
Some improvements with the objective of minimizing these impacts may be implemented based on the findings of this LCA study. Increasing the recycling content of materials like plastic and steel could be very advantageous, but this is only achievable when the recycling content exceeds 50%.

Keywords: Life cycle assessment, airbag, carbon footprint, water use, resource depletion.

Table of Contents

Table of figures

List of abbreviation

ADP Abiotic Resources depletion

CLM 2001is an impact assessment method

DMT Dimethyl terephthalate

Dtex: Decitex: Decitex is the count grading for filament and spinning yarns

ECU electronic control unit

GWP global warming potential

ISO: international standard organisation

LCA life cycle assessment

LCIA life cycle impact assessment

PAB Passenger airbag

Midpoint indicator: during the impact assessment phase, this indicator concentrates on a single environmental problem such as global warming, ecotoxicity etc.

Endpoint indicator: during the impact assessment phase, show the environmental impact on three higher aggregation levels, 1) effect on human health, 2) biodiversity and 3) resource scarcity.

1 Introduction

In 1987 the United Nations Brundtland Commission defined sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 2022). The world population today is 7.8 billion people, and it is expected by 2050 the population will be 9.9 billion people (PBR, 2020). Therefore, the current generation has the ethical responsibility to confront today’s environmental challenges and ensure to leave enough resources for future generations.

During the last decades, environmental problems have gained more and more attention, and there is more awareness about how human activities have affected and caused damages to the environment. The amount of carbon dioxide and other gases emitted by human activities have been increasing drastically since the Industrial Revolution (BBC, 2013).

Anthropocentric activities such as burning of fossil fuels, deforestation for agriculture and grazing livestock have contributed not only to global warming but also have caused other damages to the environment (Europeiska kommissionen, 2022). The unbalance in the greenhouse gases has tremendous consequences on the planet’s weather, the climate system, and on the planet’s biodiversity (Nunez, National geographic, 2019)

While material and energy are essential for human survival, it is also true that the consumption of these resources has increased enormously in recent decades, to the point of over consumption. The challenge today is how to cover the needs in products and services for 9 billion people in the near future, that is why it is necessary the consumption needs to be steered in a more sustainable direction so it will not harm the planet. Scientists in different fields are responsible for improving or developing new technologies, finding new materials, new energy sources and recycling processes to make better use of the planet’s resources.

1.1 Background

It is known that the automotive sector encounters significant environmental challenges not only when it comes to fuel consumption, with respect to emissions during the user phase because of the combustion of fossil fuels, but also during the manufacturing processes. During the last decades, the transportation systems has become one of the largest contributors to poor air quality, noise pollution and climate change (Nunez, National geographic, 2019) (European Environmental Agency, 2022)

The transport sector consumes 30,8% of the total energy consumption in Europe (Eurostat, 2019), and it is among the most significant sources of greenhouse gas emissions, producing around 15% of the total European carbon dioxide emissions (figure 1) (European Commission, 2011). The reduction of emissions in the transport sector is one of main policy goals in Europe, looking for more sustainable technology in the sector (European Environmental Agency, 2020)

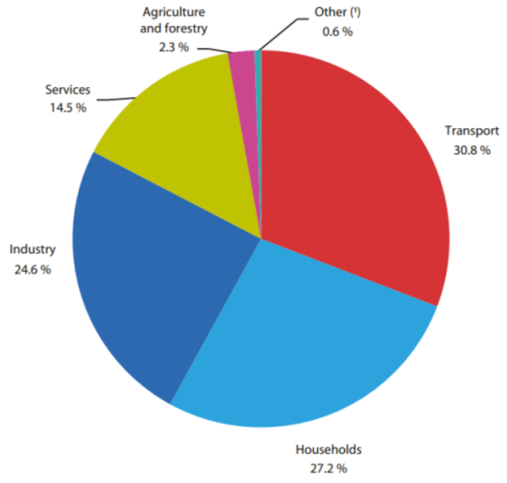

Figure 1 Final Energy consumption by sector, EU-28-2017 (16)

Volvo Cars is a multinational manufacturing corporation headquartered in Gothenburg, Sweden, the company is conscious of being responsible and acts to meet not only safety standards, but also sustainability standards in terms of minimising the impact that its products may have on the environment. The company aims to reach carbon neutrality by 2040 (Volvo Car Corporation, 2022), and in order to support this commitment, the company plans to reduce their carbon footprint in its products (Sustainability Centre Volvo Cars, 2021).With the help of life cycle assessment, they can have a deep understanding of the environmental performance of some of their products.

2 Theory and literature review

2.1 Life Cycle assessment

Life cycle assessment is a method to assess the environmental impact of a product or a service across its life cycle. A life cycle assessment (LCA) follows a product from its extraction as raw material, through production and use until its disposal (Baumann & Tillman, 2004). The method provides a holistic view of the life cycle of a product rather than information about separated processes.

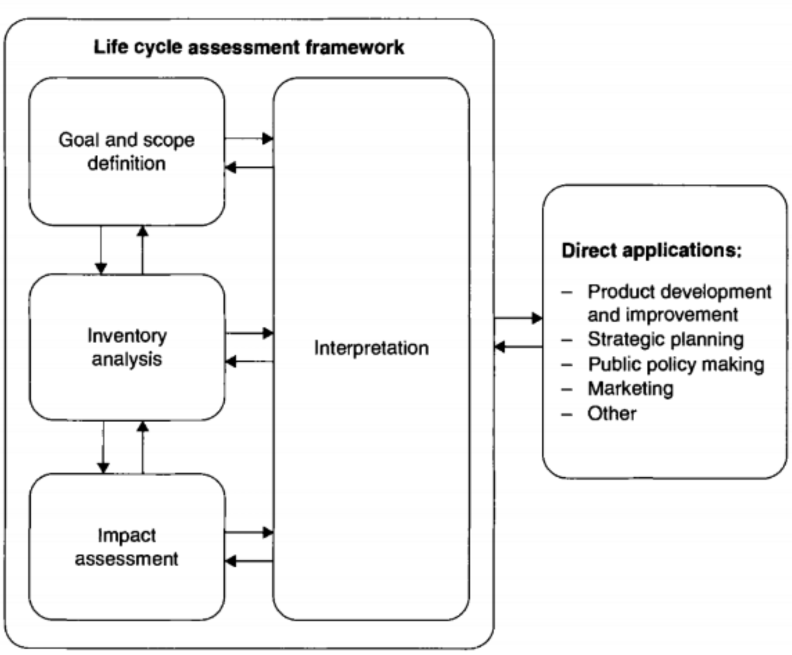

Figure 2 General methodology framework for LCA (ISO 14040)

The master thesis has followed the steps described below in the performance of the Life cycle assessment: (ISO 14040, 2022)

- Goal and scope definition: in the first step the specification of the product, the intent application and the purpose or reason of the study is determined as well as the system boundaries are defined.
- Inventory analysis: in this second step, the model is constructed based on the boundaries that were defined in the first step.
- Impact assessment (LCIA): indicates the impacts of the environmental loads described and quantified in the inventory analysis.
- Interpretation of the results.

2.2 Literature review

The following chapter presents a selection of research papers about alternative materials for airbag components such as the bag and the housing and a LCA study on a driver's airbag.

Mujiyanto and Priyojati (2010), in their thesis, have studied the environmental performance of a pyrotechnical driver's airbag "cradle to grave". They have focused on environmental impacts such as Global warming potential, Acidification, Eutrophication, Resource Depletion, Aquatic Ecotoxicity and Human Toxicity. The results showed that processes that have larger impact on the environment in the whole life cycle of the driver's airbag are steel and polyamide productions and the entire life cycle for one airbag produced 4,93 kg waste, consumed 569 MJ, and required 79 kg water (Mujiyanto &Priyojati, 2010).

Many of the research papers that examined alternative materials for the airbag's bag suggested PET plastic as a good alternative material.

Guifen Yao (2015), in his article explains that polyamide 6.6 has always been the most traditional material for airbag fabrics, it is a material that meets the requirements for the fabrication of airbags, but polyester filament demonstrated similar characteristics in terms of mechanical and thermal properties, and it can be considered an equivalent material as polyamide 6.6 (Guifen, 2015).

Nyström and Olsson (2013), in their thesis, have investigated the possibility of using alternative materials for the fabrication of airbag's cushions. The objective was to understand different characteristics of textile materials and study the possibility to change materials in the fabrication of airbag's cushions and with optimise cost. The results showed that one of the samples of PET tested could be used as material for bag's fabrics (Nyström & Olsson, 2013).

Orme et al. (2014), have made a comparative study about the use of PET in place of polyamide 6.6 for airbag's cushions. They affirm that PET and polyamide 6.6 are materials that present differences, but improvements in PET have made the material attractive to use as cushions fabrics. They concluded that PET can be a suitable material for the fabrication of airbag's cushions in certain conditions, for example, if design modifications are made so that the product meets the necessary requirements.

Alternative materials for housing's production were also examined throughout the literature review. Because of its light weight and other characteristics, some studies suggested using magnesium in various components of a vehicle, as for example for airbag's housing. (Orme, Walsh, & Westoby, 2014).

Yang Jin et al. (2000), propose in their research, the possibility of using magnesium alloy in the fabrication of passenger airbag's housings. They have compared different alternative materials for plastic's housings in terms of weight, and it has been shown that magnesium is much lighter and the fabrication of magnesium housing results in considerable weight savings. They conclude that die-cast magnesium alloy offers a greater degree of design freedom, and that magnesium is an optimal option for passenger airbag's housing, saving approximately 1 kg in weight. These findings are advantageous when considering current environmental regulations and the increased demand for fuel-efficient lightweight vehicles. (Yang, Ko, Lim, Hyun, & Lee, 2000).

Kumar et al (2000), explain the advantages of using magnesium alloys as material in automotive and in aerospace due to the increased interest for lightweight materials. In their study, they explain the connection between the use of light materials in vehicles and the reduction in the carbon footprint. (Kumar, Phanden, & Thakur, 2021)

On the contrary, Witik et al. (2011), in their study, have evaluated and compared several lightweight polymer composites with magnesium and steel with the objective to assess life cycle costs and environmental performance. According to the results of this study, reducing weight will not always improve emissions to the environment. Lightweight materials such as carbon fibers and magnesium have been shown to have negative environmental effects during their lifetimes. The environmental burdens are associated with the extraction of the raw materials and the manufacturing processes, the reduction in CO_2 eq. has been only observed during the "use phase" (Witik, Payet, Michaud, Ludwig, & Månson, 2011).

According to the literature review, PET and magnesium seem to be good alternative materials for manufacturing of airbag's components such as the bag and the housing. Magnesium may be a good option for lowering emissions during use phase of vehicles due to its light weight but generating more emissions during its extraction and manufacturing. Technically, PET seems to be a suitable material for airbag's cushions, however, if some modifications are needed to meet the product's functions, adding other substances will likely affect its environmental performance. From a technical perspective, both PET and magnesium are considered to be good alternatives; however, it is still necessary to investigate more about the environmental impact of these materials to decide if they can be considered sustainable.

The literature review also prompted the idea of designing a scenario for the bag's production using PET rather than polyamide 6.6. The material magnesium, which is used during the production of the housing, was not modelled for the scenario analysis due to a lack of information regarding the amount of magnesium needed for this production.

3 Goal and scope definition

3.1 Goal of the study

The aim of the study is to analyse, assess and provide relevant information regarding the environmental performance of a car airbag during its manufacturing process. With this commitment a Life Cycle Assessment has been performed from cradle to gate for each of the ingoing parts of a passenger airbag (PAB).

The study included raw materials acquisitions, materials production and refining, manufacturing processes of all the airbag's components, the assembly of all the components in the airbag module, until the final product came to the Volvo fabric site in Gothenburg Sweden.

Research questions:

- Which part of the life cycle of the product in terms of materials, energy or manufacturing processes have a larger impact (hot spots) on carbon footprint, water use and depletion of natural resources?
- What kind of improvements are possible to consider after the identification of hotspots in the sense to reduce those environmental impacts?

The reason of this study

The company has the objective to reach safety, quality, and sustainability standards, they want to lift sustainability aspects as important as quality and safety. Airbag and Steering Wheels' team at Volvo is aware of the necessity to evaluate their products from a sustainability perspective and will, therefore, conduct a life cycle assessment of one passenger airbag (PAB) as a starting point to get a better understanding of the environmental impact of the product.

The audience of the study is the Airbags and Steering Wheel team, the Sustainability Centre at Volvo Cars, automotive suppliers, and the public in general who could be interested in the subject.

The results of the LCA study will be used by the Airbags and Steering Wheel team to understand the impacts that the airbag's production may cause to the environment, which part of the airbag's production contributes most to those impacts and how the impacts can be reduced. The results will also be used by the Sustainability Centre as an input when Volvo cars conduct LCA studies of complete vehicles.

3.2 Scope of the study

Product description

Airbags are safety instruments specifically designed to protect automobile occupants from injuries during an accident. During a collision, airbags inflate to protect the passenger's head and deflate afterwards to prevent a rebound effect (Autojosh, 2022). There are various types of airbags depending on the type of vehicle, in general, modern cars have many airbags installed in strategic places as side-airbags (including in seats), curtains airbags, or frontal airbags. (Bellis, 2019). A typical airbag is a module which contains a bag, a gas generator and cables that are connected to the ECU “electronic control unit” that sends the signal for the activation of the airbag. Research studies show that in case of accidents the use of airbags reduces the mortality in a 32% and the use of the combination seatbelt plus airbag can reduce the mortality in a 67% of the cases. (Cummins, Koval, Cantu, & Spratt, 2011)

Airbag’s function is to slow down forward motion of the car's occupants in case of collision, thereby protecting them from severe injuries on the chest and head (Audi, 2006). When an accident happens, the car reduces its velocity, this deceleration must be great enough so the sensors can detect this sudden deceleration. The sensors send an electrical signal and activate the initiator that ignites a gas generator (Autoliv, 2022). The initiator contains a wire that heats the propellant inside the chamber, with this a chemical reaction occurs, this reaction generates gas that inflates the airbag. The airbag is inflated in the range time between 30 to 40 milliseconds. The function of the airbag, when inflated, is to absorb the energy from the forward movement of the head and the upper side of the body and distribute it to a larger area, this function helps to protect the person from injuries during the crash. After 120 milliseconds the gas is vented from the airbag through small openings in the bag.

The passenger airbag (PAB) is situated into the dashboard (figure 3), and it is composed of the bag unit, the gas generator with the explosive device, the housing, wire harness for cables, and other minor parts for the assembly like bushings and nuts (figure 4), the product does not include any electronic parts. The passenger airbag (PAB) studied in the Master Thesis, is the frontal passenger airbag for the car model Volvo XC90.

Figure 3 Passenger airbag front side installed in the car’s dashboard

The main parts of the airbag module (PAB) (figure 4) are the bag, the housing, the wire harness and the inflator, other small parts are bushings, nuts, sealing cap and the label.

	Airbag components
1	Inflator
2	Bag
3	Housing
4	Bushings
5	Sealing cap
6	Nuts
7	Label
8	Wire harness

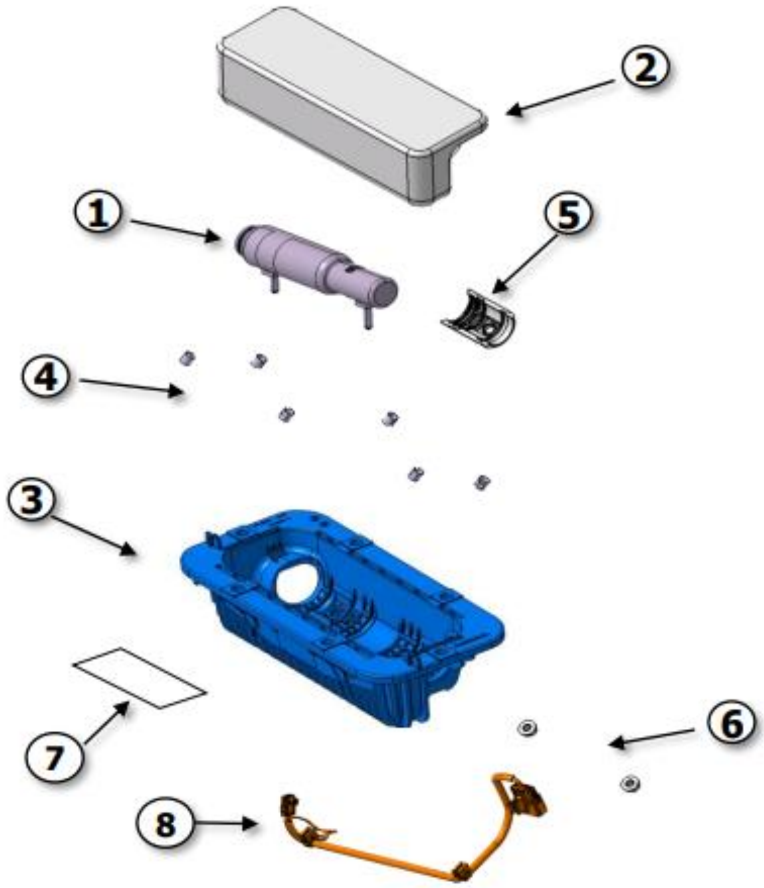

Figure 4 Main components of a passenger airbag

Functional unit

The functional unit of the study is "one passenger airbag module (PAB)" and the reference flow is "the total mass of one airbag module produced with all its parts". This functional unit was considered a good option because it is precisely defined (one module) and measurable (the PAB module total weight is 1,99 kg). Moreover, "Airbags and Steering Wheel" team is concerned about the sustainability aspects of the airbag, its components, and its entire manufacturing process. Besides the fact that the PAB module is produced by one supplier, and several components are produced in-house, making the task of gathering information easier.

System boundaries

The study included the acquisition of the raw materials, refining and manufacturing processes, the technical boundaries include materials, energy, and transportation (inflows-outflows) for the manufacture of the airbag components, the assembly of the module, and transportation of the final product (PAB) to the Volvo factory in Gothenburg. A general flowchart for the passenger airbag production with all its components is shown in figure 5, the technical boundaries for the manufacturing of the airbag are delimited in red lines.

The geographical boundary is Europe, and the data collected is the suppliers' current production over one year.

The life cycle inventory will not include data from infrastructure and capital goods as machinery or personnel food or transportation (Baumann & Tillman, 2004)

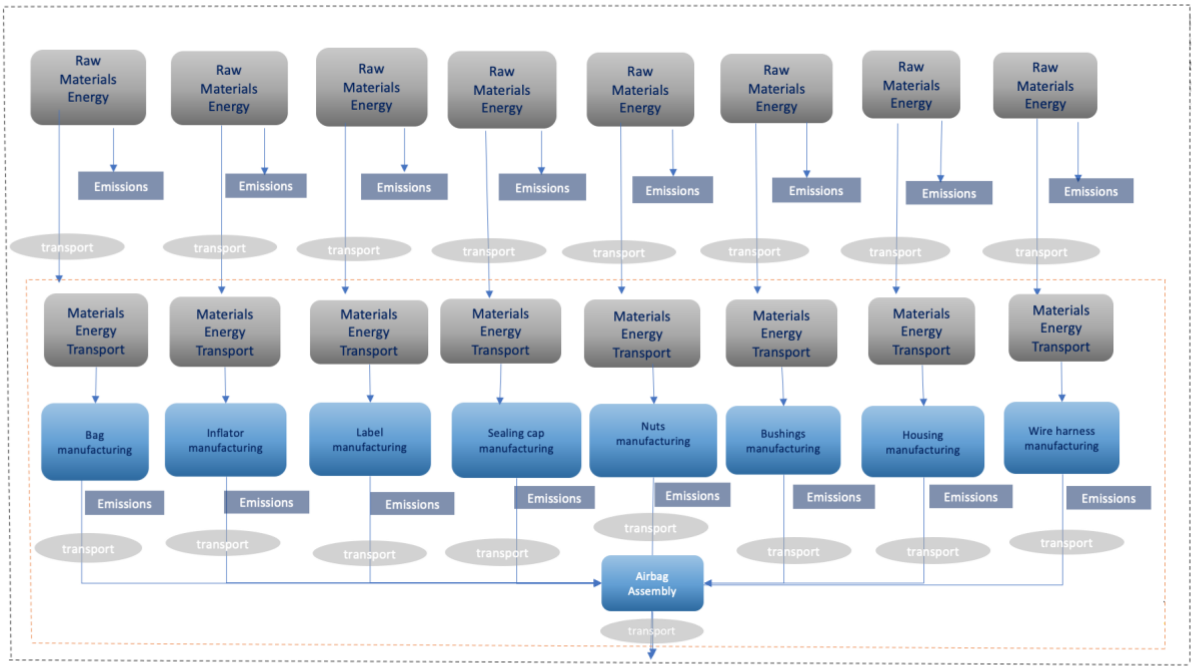

Figure 5 General flowchart for the airbag production.

Choice of the impacts categories and method for impact assessment

The study focused in three environmental impact categories:

- Global warming potential (GWP 100 years)
- Abiotic resources depletion (ADP)
- Fresh Water Consumption

Global warming potential refers to greenhouse emissions that intensify the radiative forcing in the atmosphere, that means these gases absorb infrared radiation and warms the atmosphere. Carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide are some of the gases in this category that may cause climate change. (Baumann & Tillman, 2004). Global Warming Potential was selected since the company intends to investigate the carbon footprint of their products; therefore, it was the most relevant impact category for this study.

It is the company's purpose, in a near future, to continue expanding the study of sustainability aspects of its products, that is why other impact categories were included in this LCA study such as Abiotic Resource Depletion and Freshwater Consumption.

Abiotic Resource Depletion are physical non-living resources such as metals ore, crude oil, wind energy production etc. and it is calculated in kg Antimony (Sb) equivalent. This model is based on natural reserves of resources, that is the concentration of the elements in the earth crust and the extraction rate of these resources (Leiden university, 2002). This impact category has been included in the study with the objective to see how materials used in airbag production affect the extraction and depletion of natural resources.

Due to problems associated with water scarcity, droughts and changing patterns of weather and water due to the climate change, the use of freshwater in the airbag manufacturing was also considered as an interesting topic to investigate.

The characterization methods chosen for the impacts assessment are CLM 2001 and Recipe 2016. CLM 2001 characterization methods is a quantitative method for impact assessment, results are classified into midpoints categories based on common mechanisms for example Global warming, Ecotoxicity etc. This method was developed by the Institute of Environmental Sciences of Leiden University. (Sphera, 2022). Recipe LCA is a method for impact assessment and was developed by RIVM, CLM, Pre consultants, Radboud University of Nijmegen and CE Deft, this method is a fusion of two different methodologies as CML and Eco-indicator. (Sphera, 2022).

Data collection

The data collection was mostly site-specific, one airbag supplier has contributed to the data collection, and all the chain production has been investigated. General data was used for information that was difficult to obtain, that the greatest possible resembled the origin of the materials in terms of geography and time. An Excel-file, that can be found in appendix A, was designed to collect site-specific data in order to cover the information that was necessary for the study. General data was extracted from a recognized database as Sphera, and the calculations have been made with the software program GaBi.

The first stage in the data gathering phase was to contact suppliers, which was done via chat-conference, and it was explained the benefits of a LCA study. Secondly, the supplier company formed a team that had the task of handling contact with sub-suppliers so the data collection could be obtained rapidly.

Some data was easy to collect, as for example for the manufacturing of the bag and the inflator other data was difficult to obtain as for example the wire harness manufacturing, the housing due to those productions taking place outside Europa.

Assumptions

The lack of site-specific data about some processes led to some assumptions, these assumptions were considered as uncertainties.

The first assumption was with respect to the distance for the transportation of waste and material to be recycled to its destination to municipal waste or recycling centres. The lack of information led to the assumption that the distance to those places could be 50 km, later this data was tested in the sensitivity analysis

Another assumption was with respect to the pyrotechnics in the inflator, since it was confidential information, a similar chemical from general database was used in the modelling of this process.

Since wire harness' production takes place outside Europe, it was difficult to obtain specific data regarding this production and the time constraints made it necessary to use generic data. With specific data that suppliers provided, the model was built based on the materials and weight of the wire harness components, and for upstream processes generic data was used.

Since upstream processes for the housing's production also occur outside of Europe, some assumptions had to be made in this case. In absence of generic data for the specific geographic production, it was assumed that electricity played the biggest role in global warming as an environmental impact during the life cycle of any product. Thereby, it has been compared electricity production in different countries where general dataset for this process existed, in order to choose the most suitable data for the production in question.

Limitations

Limitations arose because some data from upstream manufacturing processes was difficult to collect. It was therefore necessary in some cases to make some assumptions, while in others, data from general databases was used.

4 Inventory analysis

An inventory analysis was constructed using specific information about inflows and outflows of all the materials, type and amount of energy, type of transportation, distance for the transportation, countries of origin of the raw materials, manufacturing process for each of the airbag's components, and assembly of t airbag, all these information were provided by suppliers. Generic data were used for processes for which site-specific data was not available. Because of confidentiality concerns, detailed information, such as the amount of the raw material, the countries from which the raw material was extracted, or in some cases upstream processes couldn't be disclosed in this thesis. Accounting for the different types of emissions generated by all these processes and the calculation of all the input and outputs were part of the modelling in the LCA software program.

Technical description of the processes and components

4.1 Bag

The bag is made of a woven fabric that can be made in different shapes depending on the requirements of the vehicle. Fabrics used for airbags must resist the force of gases and must not allow them to penetrate the fabric. Polyamide 6,6 high-tenacity multifilament fabric is typically used for airbag's cushions (Behera & Hari, 2010). The fabrics have different density of the yarn (dtex), the designations dtex characterise the density of the yarn per dm^2. The bag is inflated by a mixture of gases, and it takes 37 milliseconds to be fully inflated, its function is protecting the passenger of serious injuries when a collision happens.

Figure 6 Driver's airbag fully deployed (Euroncap, 2022)

Figure 7 Passenger and driver's airbag fully deployed (Euroncap, 2022)

Bag flowchart

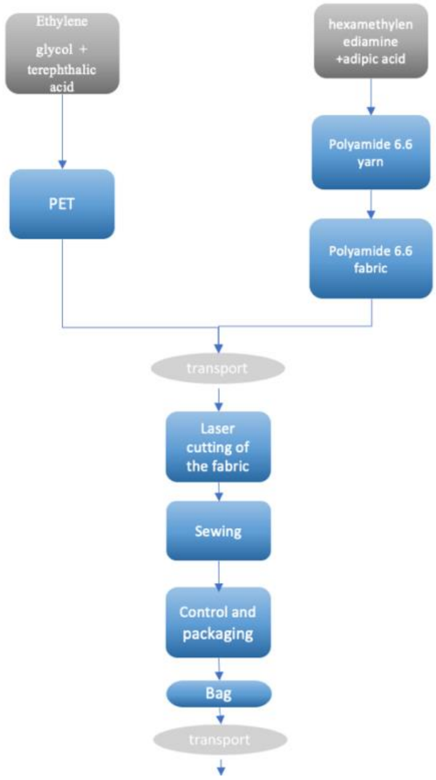

Figure 8 Flowchart for the manufacturing of the bag

Raw materials and their manufacturing

Polyamide 6.6 is synthesised through polycondensation of hexamethylenediamine (monomer) and adipic acid, which results in a chemical reaction that creates polymers from monomers. During the manufacturing process, the polymer has a form of a salt, this salt is heated until it becomes molten. The molten material is placed through a metal spinneret, a process known as studding, a process that involves a large amount of water and then the polymer is solidified. Afterward the material is spun into fibre, it is loaded onto a bobbin, and stretched to increment its strength, then the material is wound in another bobbin, once this is done, the fibre is prepared to be spun into a textile. Polyamide fibres require between 7 and 8 MJ of energy per kilogram fiber (Swicofil, 2022), (Sphera, 2022)

Polyethylene terephthalate (PET) is other of the raw materials used in the manufacturing of the bag; PET is produced in a vacuum by transesterifying dimethyl terephthalate (DMT) with ethylene glycol as raw materials followed by a polycondensation reaction. The process includes spinning of PET and surface treatment with epoxy resin sizing agent. PET fibers require between 0.3 and 0.8 kilowatt hours per kilogram fiber. (Sphera, 2022). The data for polyamide 6.6 and PET processes were gathered from the Sphera database.

Bag's manufacturing

The production of all the materials required for the fabrication of the bag takes place in Europe and they are transported by trucks of 40 tons capacity to the assembly's place. The nylon fabric goes into the manufacturing in rolls of 1000 metres, shaped and measured precisely with laser cutting and sewing to meet the desired requirements. Polyamide 6.6 fabrics' waste from the production goes to recycling and PET waste from production goes to incineration. Finally, the product undergoes quality control and after this the product is ready for packaging and shipping to the airbag's assembly place. This data was site-specific data and was provided by suppliers.

4.2 Inflator

There are different types of inflators for airbags, one of these is the pyrotechnic inflator which generates the gas through a chemical reaction. Other inflators have storage compressed gas, and this gas is released to inflate the airbag. A third kind of inflator is a hybrid inflator, this inflator uses a combination of gases and a solid material propellant that are stored in the container, this was the inflator modelled in this LCA study. The initiator is activated in response to a sensor that give a signal, the process starts when the propellants burn, the pressure of the gases increases because of the high temperature in the chamber, and finally it escapes from the outlets which are used to inflate the bag (United States Patentnr US5031932A, 1991).
The following sequences of pictures were taken from a film provided by the supplier, to demonstrate how the inflator activates.

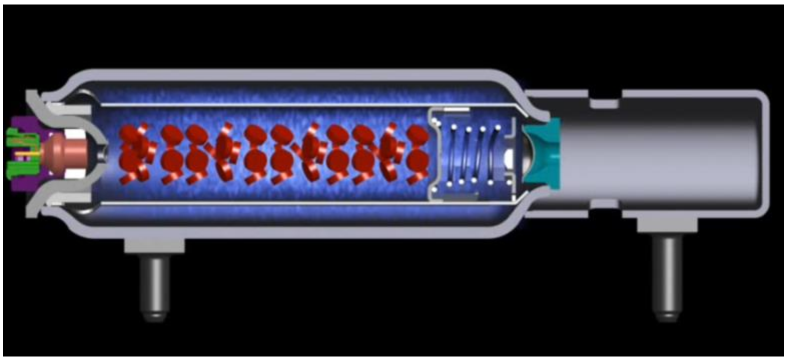

Figure 9 Inflator filed with gases and propellant

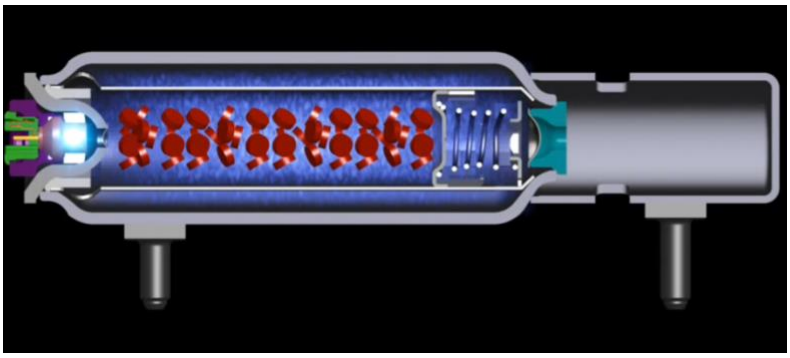

Figure 10: signal and ignition

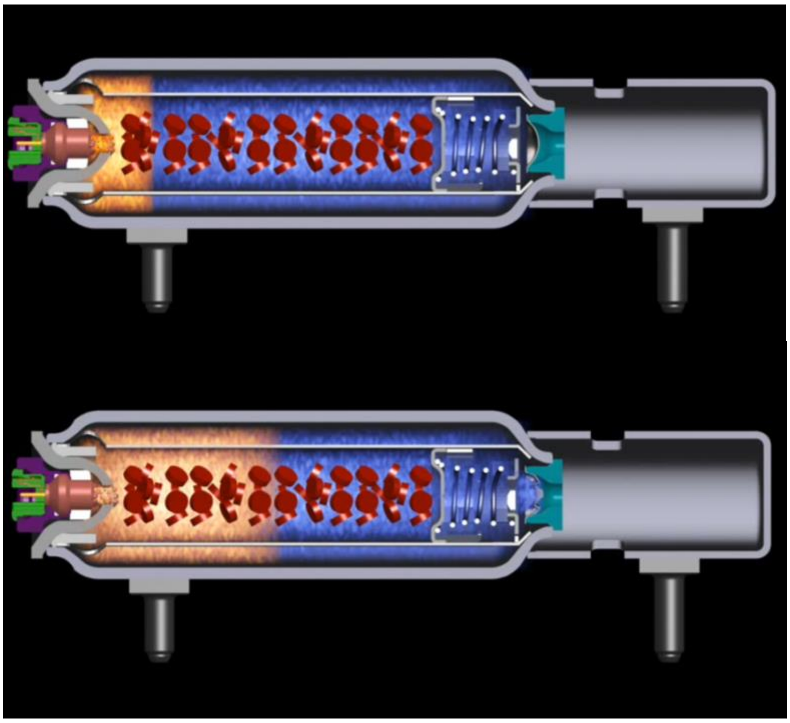

Figure 11: the ignition of the propellants causes temperature and pressure increase

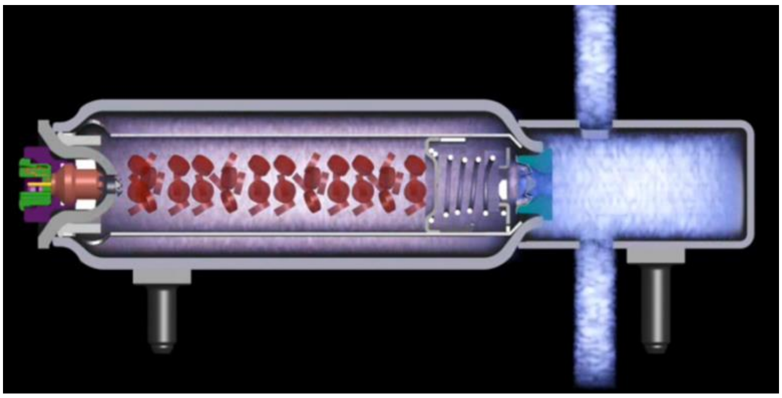

Figure 12: the gases release

The bottle, the diffuser, and the combustion chambers, which are three of the major parts of the inflator, are made of steel. There are other components such as gases like argon, helium and oxygen, pyrotechnics and small parts made of plastic and steel. Site-specific data for all the inflator components and their manufacturing processes (inflows and outflows) was provided by the supplier, while general data sets were used for the upstream processes, including steel, pyrotechnics, rubber, and gases' production.

Inflator Flowchart

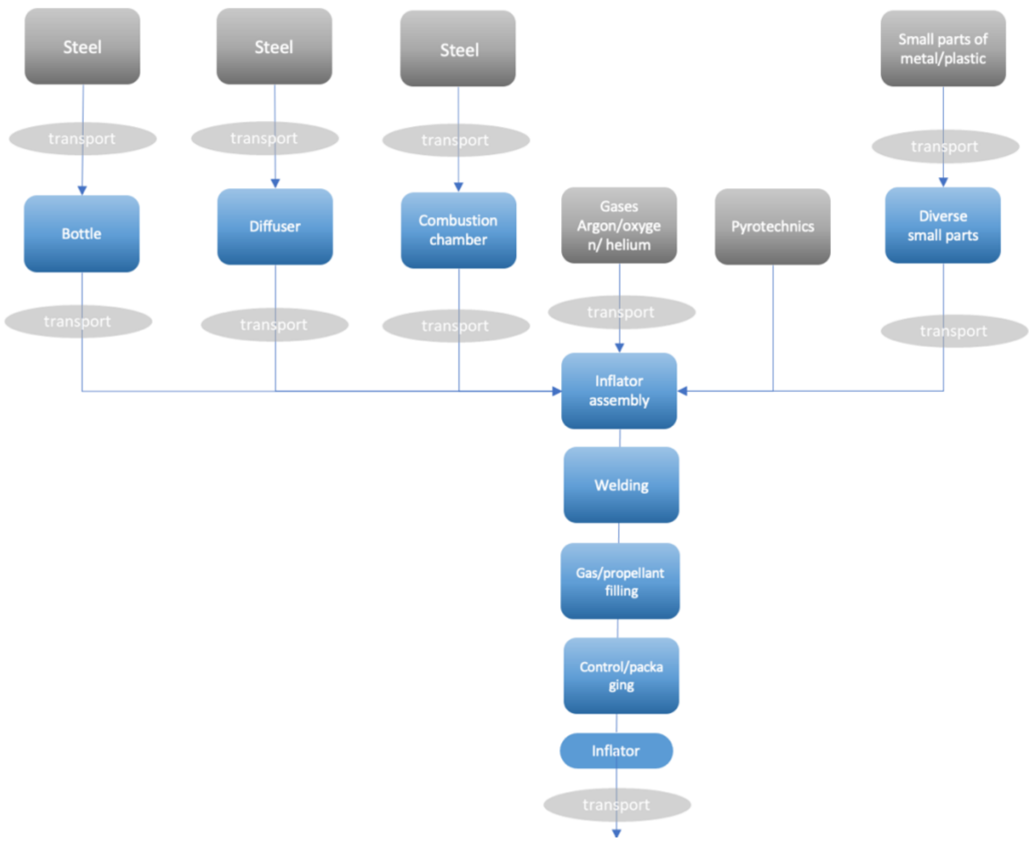

Figure 13 Flowchart for the manufacturing of the inflator

Steel manufacturing

Steel is an iron alloy, this means that it is a metal that has been combined with at least other metals or nonmetals elements, it is primarily composed of iron and contains no more than 2% carbon. The main raw materials in the production of the steel are iron ore, limestone, coal, scrap, and energy. In a Sinter plant, the ore is crushed and mixed with the limestone coke breeze, slag-forming agents etc. at elevate temperature. Steel can be produced via two main routes: the blast furnace-basic oxygen furnace (BF-BOF) route and electric arc furnace (EAF) route. The electrical arc furnace method uses mostly recycled steel that is melted by heating by power electric arc, during this process different elements are added to reach the desired properties of the steel as purity. In the blast furnace-basic oxygen furnace (BF-BOF) method, the steel is made through oxidation by injecting oxygen. After this, a process called continuous casting takes place, steel is solidified, then the steel is cast in three semi-finished shapes: slabs, billets, and blooms. (World Steel Association, 2017)

Gases (oxygen, argon, helium)

Cryogenic air fractionation is primarily performed with the LINDE process, Oxygen in liquid state is produced by this process, the air is cooled under its critical point (Temperature = 132,5 K, Pressure= 37,7 bar), when the air is cooled a separation by rectification take place, in the rectification column the components of the air are separated by difference in their boiling points. Separation of the different gases occur, the oxygen is extracted from the bottom of the column, nitrogen from the top, and argon is taken from the middle of the column, the final products are stored in gaseous state (Sphera, 2022).

Pyrotechnics

Pyrotechnics used in the inflator consist of a solid propellant, whose formulation was part of the confidential information of the company and for that reason couldn't be disclosed. Because of confidentiality, one of the common chemicals used to produce explosives, ammonium nitrate $H_4N_2O_3$ was used during the modelling.

Ammonium nitrate is produced by the neutralisation of aqueous nitric acid by gaseous ammonia, there are three main unit operations in the production process: 1. neutralisation, 2. evaporation, 3. solidification (granulation). The first phase in the process is the neutralisation reaction, this phase is highly exothermic. In the second phase, evaporation, a high-concentration solution is formed, and the excess water is evaporated. Solidification, the final phase, turns ammonium nitrate into granules (Sphera, 2022).

Rubber

The main material to produce rubber is tapped latex, this is extracted from plants that contain this compound, there are between 30 and 40 percent rubber particles in latex, along with 55 to 65% water, and small amounts of protein, sterol glycosides, resins, and ash (Sphera, 2022).

The process to produce rubber is a complex process, latex is obtained by cutting a diagonal slice of bark halfway around the tree and approximately one third in thickness, and the flowing latex is gathered in a collection container that will be emptied later. Water is removed by centrifugal force or evaporation, elevating the rubber content to 60%, after this, chemicals are added to the process with the objective of rubber particles reaching the surface. The concentrate rubber is liquid form, which can be used for adhesives, coatings, and other applications (Sphera, 2022)

Assembly of the inflator

After all the parts of the inflator are produced and transported to the assembly place, the bottle, the combustion chamber, and the diffuser are welded, then propellant and gases are added. When the parts have been assembled, the inflators move to packaging and shipping.

4.3 Housing

The housing is a rectangular plastic box, and its function is to contain the airbag and retain the airbag in the adequate position for the inflation. The most used materials for its fabrication are pressed metal or moulded plastic (United State Patentnr US 7,837,227B2 , 2010).

The housing is made of a thermoplastic polypropylene (PP) reinforced with glass fiber, the material is good against impact strength, stiffness, heat resistance, and it is a very good material for injection moulding (Matmatch, 2022). Data collection for the housing's production was mainly site-specific data, the general data set was used for upstream processes as the polypropylene and glass fibers' production.

Polypropylene production

Polypropylene is a linear carbon, is a polyolefin or also called saturated polymer, the main raw material to produce polypropylene is propene, propene is produced by cracking naphtha from crude oil. Polypropylene is obtained through polymerization processes, there are many different polymerization processes as solution polymerization, bulk polymerization, and gas-phases processes. Heat and pressure are applied to propylene monomers along with a catalyst system, during the polymerization process, relatively low temperatures and pressure are applied, and the product obtained is translucent, but readily colorable. The properties of plastic can be altered by altering the catalyst or production conditions (Sphera, 2022), (British Plastics Federation, 2022)

Glass fibre production

Glass filaments fibres is a material widely used in a variety of applications, it is an excellent material for reinforcement, thermal and electrical insulation among other applications. (Wikipedia, 2022). The manufacturing of glass fibres generates a high amount of waste per ton of product manufactured. Most of the water required for this process is for cleaning and cooling, and the use of coating materials are responsible for the larger emissions. The process is an energy- intensive process and requires high temperature, in continuous manufacturing there are no recycling processes. The principal raw materials to produce glass fibres are silica sand, alkali earth metals, carbonates and oxides, alumina, and boron. The materials are smelted in cross-fired, air-fossil fuel or recuperative furnaces. During the glass melting process, molten glass flows along refractory gas-heated canals to the forehearths. There are several nozzles in the footplate of the bushing at the bottom of each forehearth that receive the melted glass for fiberisation. A high-speed winding equipment diminishes the glass flowing through the bushing and creates continuous filaments. After this, the filaments are cooled and coated to obtain the desired properties of the filament to further applications (Sphera, 2022).

Housing flowchart

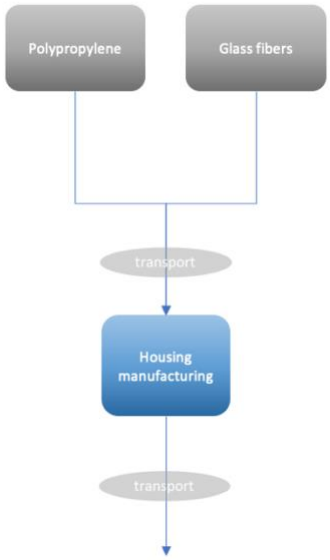

Figure 14 Flowchart for the manufacturing of the housing

Polypropylene is a good material for injection moulding with a wide range of applications (British Plastics Federation, 2022). Injection moulding is used to fabricate the airbag's housing. Plastic granules enter the machine and are transported and heated in a barrel. The molten plastic is then injected into an empty cavity of the mould, where it solidifies in a few minutes before the machine ejects the plastic part product (Todd, 1994)

4.4 Bushings

Bushings are small pieces which are used to screw the module into the car's instrument panel; the raw material is steel, and the bushings are manufactured in Europe and transported to another European city where the assembling fabric is situated.

The steel bar is cut and then the bushings are shaped in a lathe machine, this machine rotates the pieces in axle until the bushing is formed, after pieces are controlled, they are packaged and then shipped to assembly. Site specific data was used for the bushings' production and generic data was used for the steel's production.

Bushing flowchart

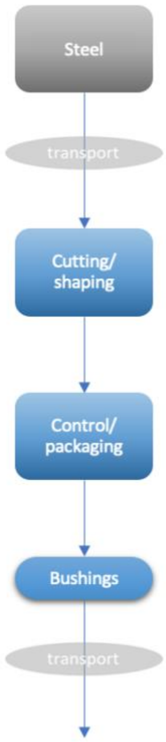

Figure 15 Flowchart for the manufacturing of the bushings

4.5 Label

This manufacturing process has many steps, and they are performed by different actors: the raw material used for the labels 'fabrication is PET granulate. PET granulate are produced from high purity ethylene glycol (EG) and Dimethyl terephthalate (DMT), (Valco group, 2021). The process consists of esterification, polymerization and palletization and crystallization.

PET granulate is used to manufacture PET film by extrusion, after this, the films are transported to the label manufacturing where the film is cut, put adhesive, and rolled. The rolls are transported to the place where information is printed on the label. Because different stages in this production were conducted for different suppliers, it was difficult to have detailed information about all the steps in this manufacturing process for that reason general data was used for this component.

Label flowchart

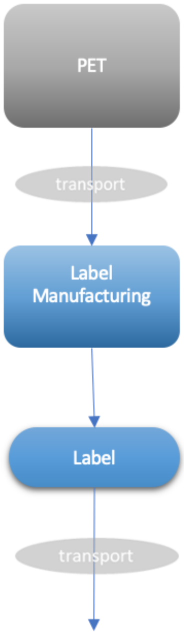

Figure 16 Flowchart for the manufacturing of the label

4.6 Sealing cap

The sealing cap is a piece in the inflator which has the function to prevent the escape of the gas in only one direction. The main raw material used in the sealing cap's production is polyamide 6.6. The manufacturing process is by injection moulding, using injection moulding, plastic materials are melted and injected into moulds, after which they are cooled and solidified. Site specific data was used for the sealing cap's production and generic data set used for the polyamide 6.6's production

Sealing cap flowchart

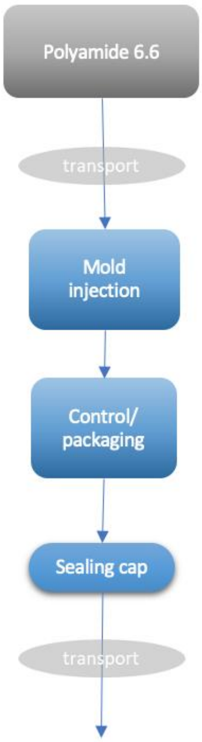

Figure 17 Flowchart for the manufacturing of the sealing cap

4.7 Wire Harness

This module contains all the cables that connect the airbag module to the car's cables that are connected to ECU (Electronic Control Unit), this is the component within the car that controls the vehicle's electrical system (Ecutesting, 2022) .

Wire harnesses have different parts that are made of different materials, and these parts are manufactured in different processes. The supplier buys this component as a whole module. The main raw materials for the wire harness are polyamide 6.6 and steel, copper, and PET. For all the upstream processing, data from databases was used, as well as site-specific data provided by the supplier, about materials and weight used in the wire harness's module.

Copper parts

The process of refining copper metal requires several steps, starting with mining and concentration of copper sulphide ores, followed by smelting and electrochemical refining to produce a pure copper cathode (USGS, 2022)

The general dataset "Copper cathode production" from Sphera database was chosen because this is the main raw material in the production of copper rod for wire and cables industry. This data set covers the copper production of the 21% of the total world production, represents 95% of the total world production on a technological level and 79% on a geographical level, including three different routes in the production: pyrometallurgical (primary), pyrometallurgical (secondary, and hydrometallurgical (primary)

The pyrometallurgical (primary) copper production, sulphide ores are mined from open pits or mines, followed by the production of copper concentrate, then this concentrate is smelted and drying converting to blister copper, this blister is refined and cast into anodes, these anodes are electrolytically refined to produce the copper cathode. Production of secondary copper (Pyrometallurgical secondary) involves pre-treating of secondary copper-containing materials, then smelted in a furnace (electrical or blast) and then producing the blister copper and finally the blister is refined to final copper cathode. The hydrometallurgical route involves mining of oxide ores, the ore is leached with sulfuric acid and solvent extraction, this creates an electrolyte solution, lastly the electrolyte solution is sent to electrowinning to produce the copper cathode (Sphera, 2022) (BMT, 2022).

Wire harness flowchart

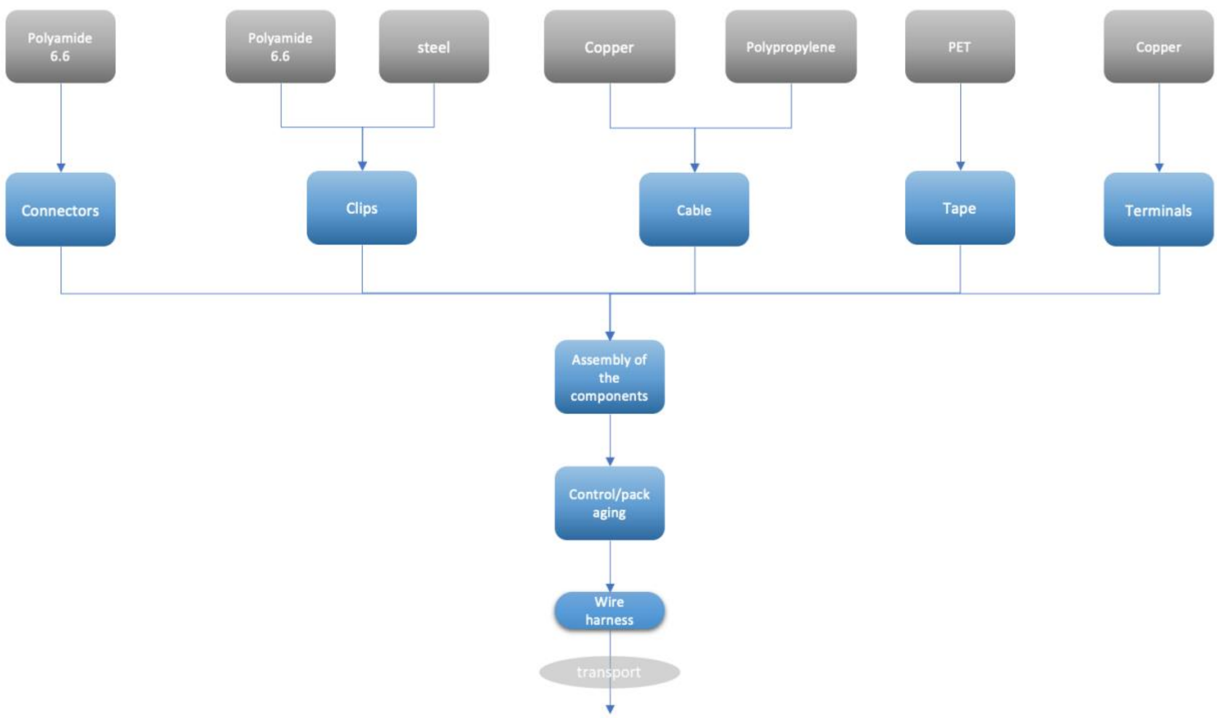

Figure 18 flowchart for the manufacturing of the wire harness

4.8 Airbag Assembly

The assembly of all the components of the airbag module takes place in a city in Europe, and it is performed in several steps, some steps are performed manually and other mechanically. The gas diffuser is manually assembled, and the inflator is manually assembled in the bag as well. Bushings and nuts are mechanically assembled at the housing, and the bag is folded in a specific way by a folding machine. After that, the bag is compressed mechanically, and the wire harness is assembled on the airbag module. The final step is the verification and control of the product, after this the module is ready to be packaged and to be transported. Site specific data for the airbag assembly provided by the supplier was used during the modelling.

5 Results and Discussion

Life cycle Impact assessment

The impact assessment provides information about potential impacts that the manufacturing of the airbags module (PAB) in terms of materials, energy use, and transportation may cause to the environment. This chapter presents the results obtained after the calculation from the inventory results, classification, and characterization.

A dominance analysis has been performed; this analysis identifies which part of the life cycle of the product contributes to the greatest environmental impact (Baumann & Tillman, 2004). A sensitivity analysis has also been performed with the objective to detect critical data with respect to uncertainties and assumptions that have been made during the building of the model. A scenario study had been carried out to investigate what kind of improvements in terms of recycling content of certain materials could be beneficial to be implemented in the future.

5.1 Dominance analysis

Global warming

Figure 19 shows the results derived from the Global Warming Potential impact assessment; the results reveal that the production of the passenger airbag (PAB) emits 10,64 kg eq. to the environment. The bag production has the greatest environmental impact regarding Global Warming Potential (GWP) with 4,59 kg CO_2 eq, followed by manufacturing of the inflator with 3,61 kg CO_2 eq. and the manufacturing of the housing with 1,61 kg CO_2 equivalent.

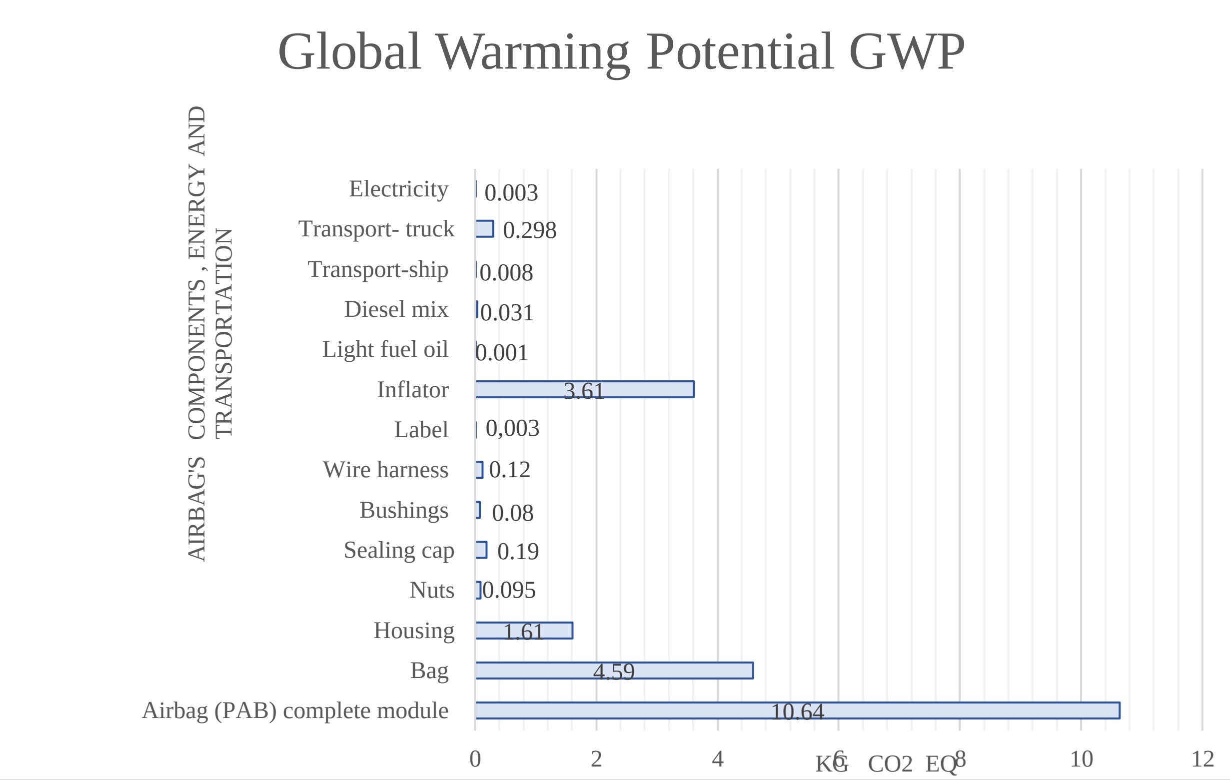

Figure 19 Impact assessment category GWP for the manufacturing of the airbag module (PAB)

The bag's high result with respect to Global Warming Potential GWP is greatly influenced by the polyamide 6.6 material used to produce the bag (figure 20). The production of polyamide 6.6 has an emission of 4,11 kg CO_2 eq. There are other contributors in this category as the electricity used for the production, transportation etc. (figure 20).

Another major contributor to the Global Warming Potential during the manufacture of the airbag module (PAB) is the manufacturing of the inflator, which generates 3,6 kg CO_2 equivalent. The main material that is used in this component is steel, the production of this material emits 3,08 kg CO_2 eq. (figure 20)

Polypropylene and glass fibres are materials that have the highest contribution with respect to GWP during the construction of the housing. The production of polypropylene is the major contributor in this impact category, it emits 0,78 kg CO_2 eq. followed by the production of glass fibres with an emission of 0,33 kg CO_2 eq. (figure 20).

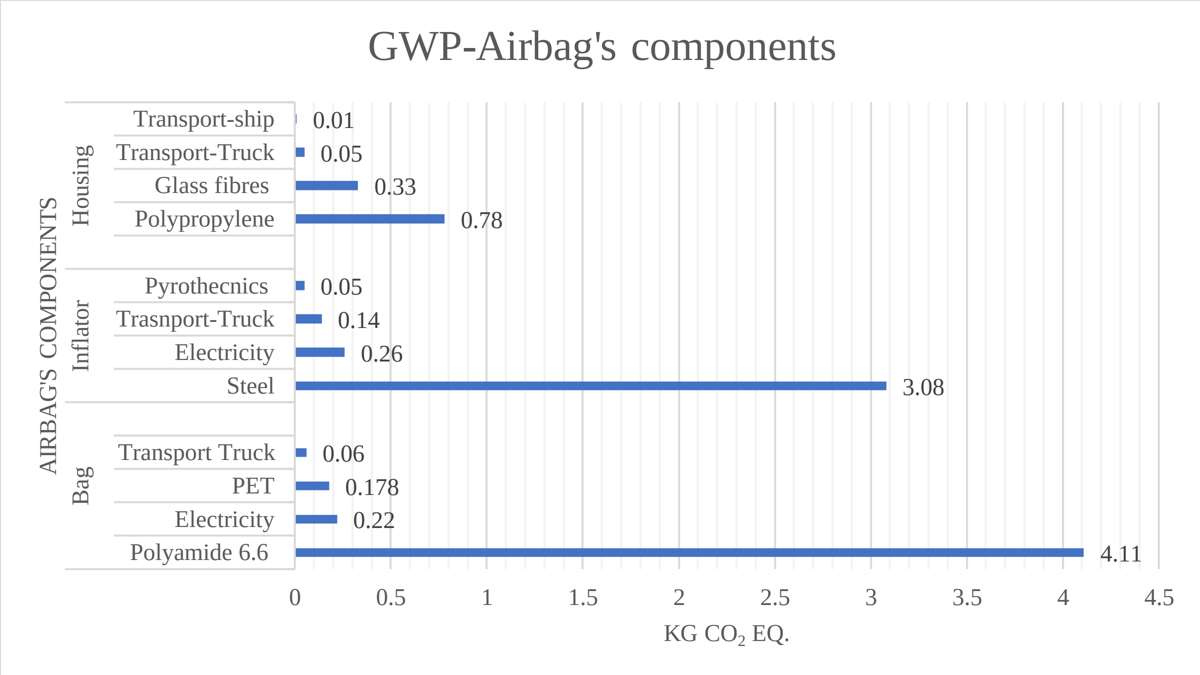

Figure 20 Shows airbag's components and materials that have the greatest environmental impact regarding to Global Warming Potential (GWP)

Some hots pots identified from the dominance analysis showed that the largest contributors for emissions with respect to global warming potential, are the production of the bag, the inflator, and the housing. Even though these components are the largest parts of the airbag, and the materials have the greatest weight and volume, the processes of extracting, refining, and manufacturing the materials, exhibit also higher greenhouse gas emissions. The highest result in terms of GWP for the fabrication of the bag is highly influenced for polyamide 6.6 production, the same results shown for the hot spots identification in the production of the inflator, the largest material used in these components is steel.

The highest impact of the housing production with respect to Global Warming is attributable to polypropylene and glass fibres, which are the processes that have the highest emissions. Polypropylene is a polyolefin, whose raw material is crude oil, its manufacturing' process is a complex process with several steps that require a large amount of heat and pressure. The complexity of the process results in large emissions in terms of GWP and resources depletion as well as freshwater consumption.

The life cycle assessment performed for the passenger airbag module (PAB) "cradle to gate" showed that the production of one airbag (PAB) for the model Volvo XC90 emits 10,64 kg carbon dioxide equivalent, results from another LCA study "cradle to gate" on a Volvo C40-recharge (global mix electricity) model, showed that this car emits 26,4 tonne CO_2 eq. (Sustainability Centre Volvo Cars, 2021). Even if the contribution to the Carbon Footprint of one PAB doesn't seem significant in comparison with the impact of the whole car and the airbag study in this LCA it is not the same as the used in the C40 model, it is important to observe that in general, modern vehicles are equipped with several airbags.

Resources depletion

For the impact category Abiotic Resources Depletion (ADP) (figure 21), the result shows that production of the airbag module (PAB) consumes 0,0277 grams antimony equivalent from different abiotic resources, being the housing the component of the airbag that requires large number of resources for its manufacturing, followed by the wire harness' production, and the inflator.

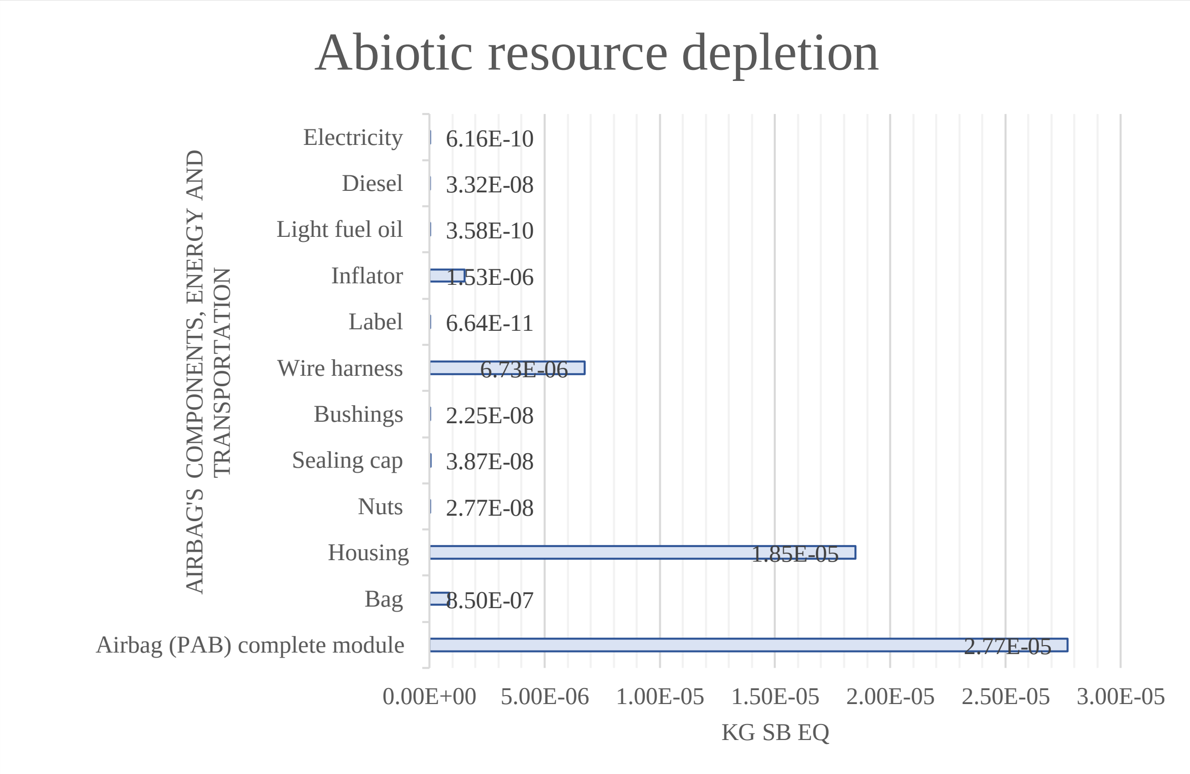

Figure 21 Impact assessment result for ADP for the life cycle of the airbag module "cradle to gate"

The housing production is the biggest consumer of natural resources, this is mainly caused by the materials used for its manufacture, glass fibre production is the material production that has the greatest impact on this category (figure 22). The production of glass fibers is a complex process, it is an energy-consuming and high temperature process, and there is no recycling in continuous manufacturing, for that reason it is a higher contributor for emissions to the environment.

The wire harness construction also requires many abiotic resources (figure 22), this component is composed mainly by cables and connectors and other minors' parts, the main materials used are copper. The copper production is one of the productions that requires many abiotic resources in comparison with other upstream processes. Copper production is a multistage, energy and resource intensive industry, that is why the wire harness manufacturing exhibits high numbers with respect to ADP depletion of abiotic resources.

For the case of the inflator the material that requires most natural resources for its manufacturing is the steel production (figure 22).

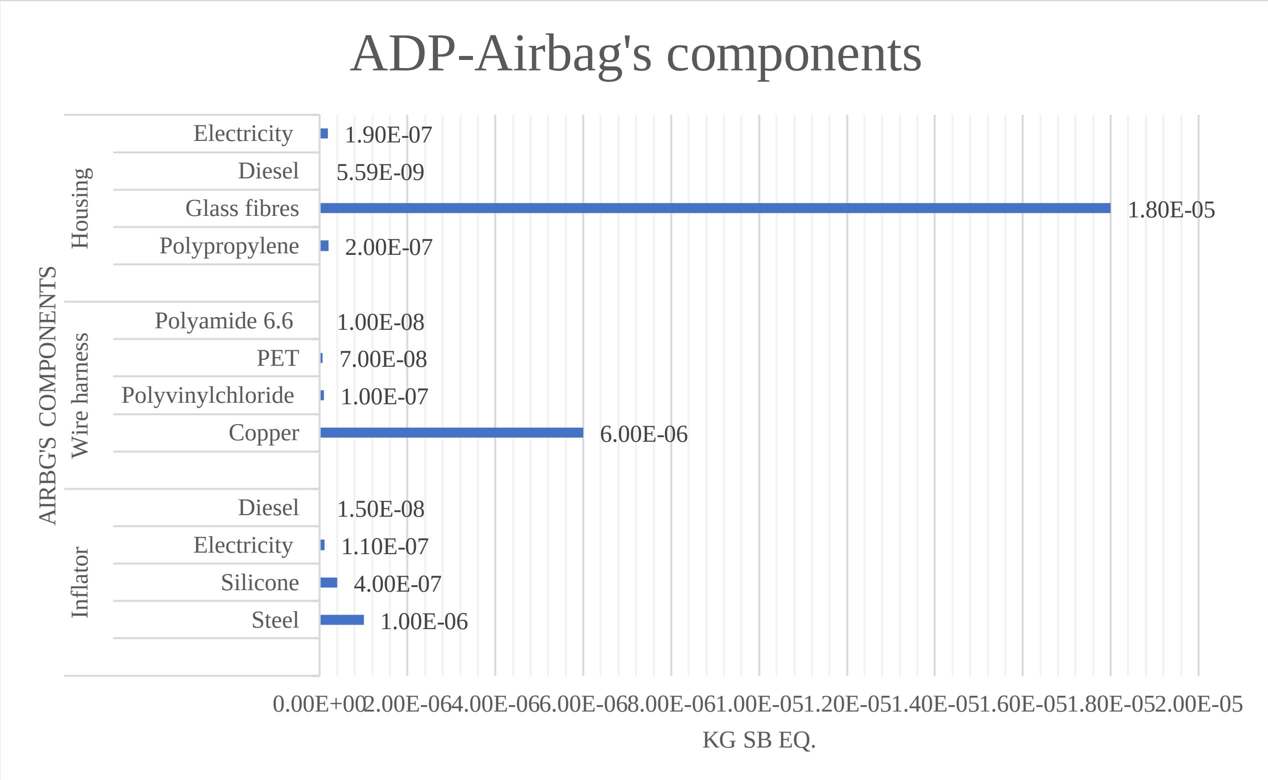

Figure 22 Shows airbag's components and materials that the greatest environmental impact regarding to ADP

Freshwater consumption

It is needed 43,8 litres to produce one airbag, and the component that requires most water is the inflator 21,05, followed by the manufacturing of the bag which requires 13,3 litres, and the housing which requires 6,18 litres (Figure 23). The high consumption of water of these components are mainly caused by the use of materials such as steel, polyamide 6.6, and polypropylene (figure 24).

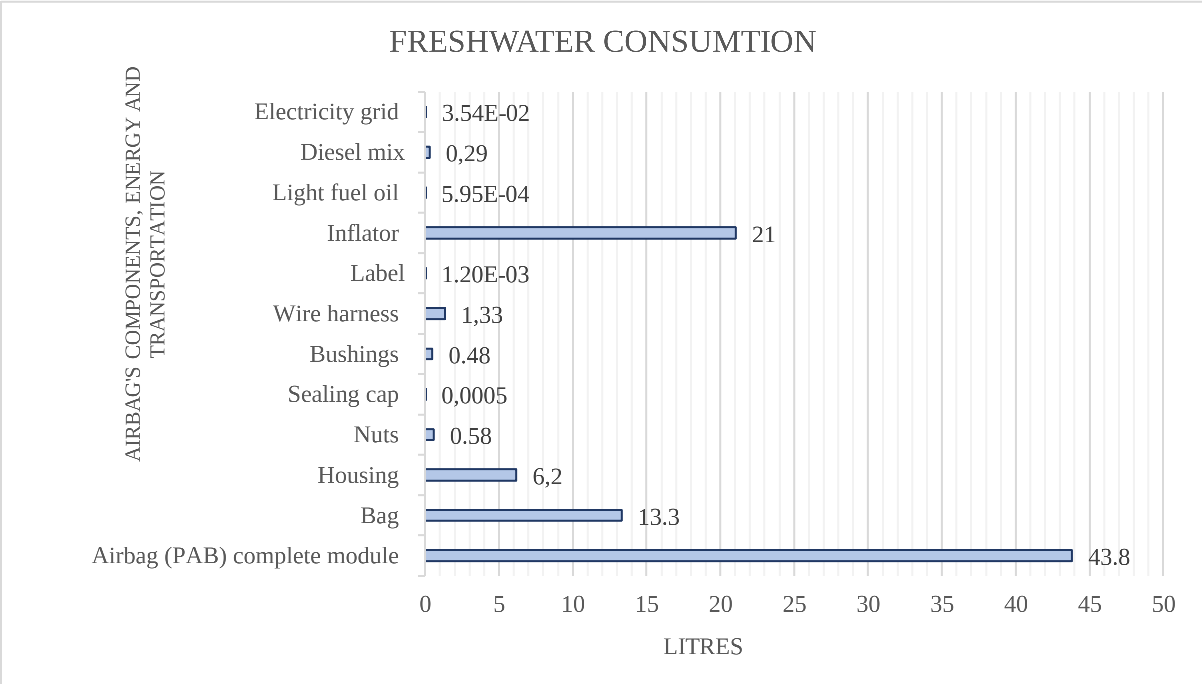

Figure 23 Shows the impact assessment for freshwater consumption category for the manufacturing of the complete airbag module and its components

The inflator is the component that utilises large amounts of water; this is mainly due to the steel production which requires 19 litres (figure 24). In the case of the bag production, the material that requires the most water is polyamide 6.6, the production of this material requires 10 litres (figure 24). For the manufacturing of the housing, the material that requires most water is polypropylene, it requires 3 litres (figure 24).

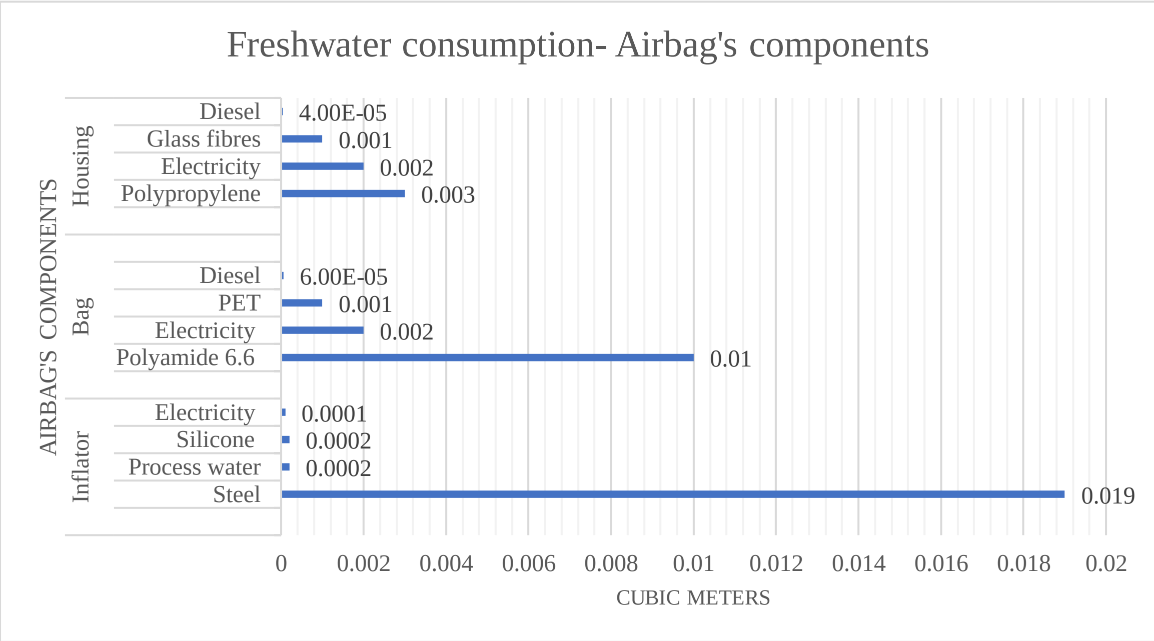

Figure 24 Shows airbag's components and materials that have the greatest environmental impact regarding to freshwater consumption

The results obtained from the impacts assessment in relation to the three impact categories analysed, indicate that the main hot spots in airbag's life cycle is the production of components like the bag, inflator, and housing, as well as the production of materials like polyamide 6.6, steel, polypropylene, and glass fibres.

The major contributors for the impact category GWP and freshwater consumption are polyamide 6.6 and steel productions, being copper and glass fibres production the major contributor for the impact category ADP. Looking at the three impact categories together, polyamide 6.6 and steel were found to be the two materials that contributed most to the environmental problem, due to their high impact in two of the three categories.

5.2 Sensitivity Analysis

The following analysis is based on the assumptions that were made because of the lack of information about certain processes.

Distance

The first assumption suggests that the distance of transporting waste and recyclable materials to their destinations, municipalities, or recycling centres, could be as long as 50 km. According to the sensitivity analysis, the change in distances didn't affect the results of the impact categories Global warming potential, abiotic resources depletion and water use.

Copper

According to the results from the impact assessment, copper has been identified as among the elements most depleted in airbag production (hotspot). The sensitivity analysis shows that the change in the copper's data sets have not influenced the results in the impact categories Global warming potential, abiotic resources depletion and water use.

Pyrotechnics

Propellants for inflators contain chemical compounds which form part of the confidential information. It is possible to obtain the same chemical through the reaction between ammonium nitrate and urea at elevated temperatures using silicon dioxide as catalyst (US Patentnr 5,041,662, 1991). The sensitivity analysis shows that the change of ammonium nitrate has not influenced the results in the impact categories Global warming potential, abiotic resources depletion and water use.

Polypropylene

The production of polypropylene was uncertain with respect to the geographical place, due the lack of site-specific data and lack of general data for this part of the world, general data from Germany was used for the modelling. For the sensitivity analysis, average data from "the rest of the world" for polypropylene production was tested.

The results didn't show significant differences between the two data sets with respect to GWP. On the contrary, depletion of natural resources increases during the production of the airbag module (PAB) by 23%, and for the manufacturing of the housing increases by 34%, when the average data set for the rest of the world was tested. Figure 25 shows the differences between the two data sets.

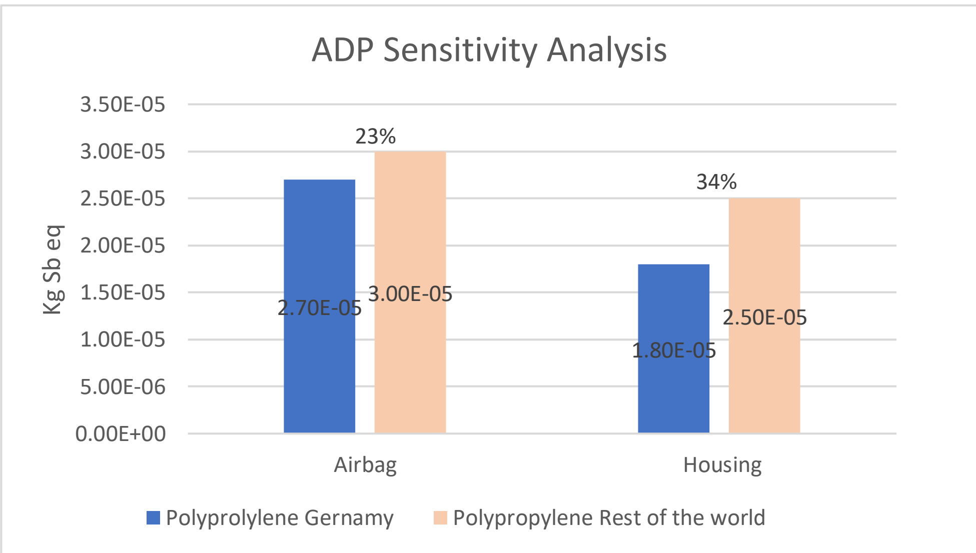

Figure 25 Sensitivity analysis for two data sets for polypropylene production with respect to ADP for the housing production and its influence in the results for the airbag module (PAB) production.

A change in the dataset increased water consumption by 14% during polypropylene manufacturing, and by 100% during housing manufacturing.

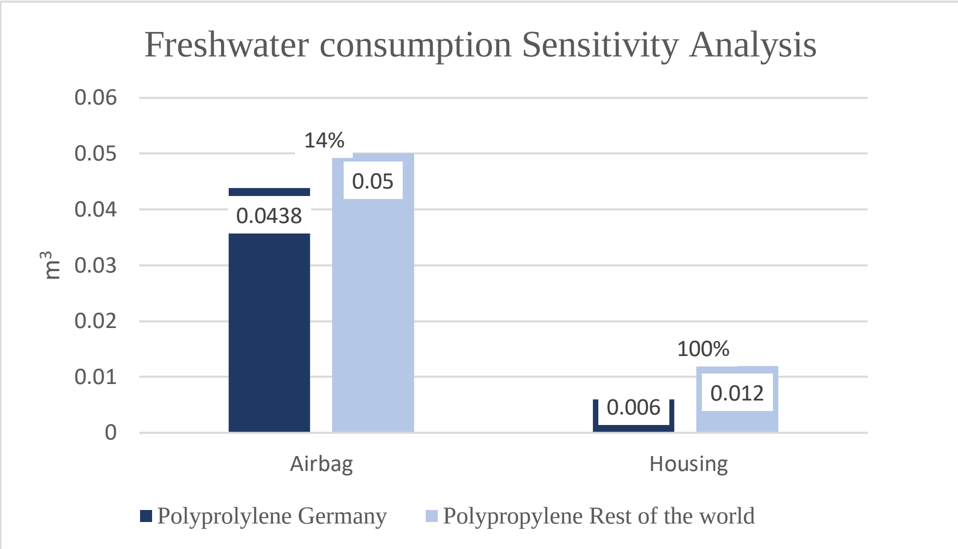

Figure 26 Sensitivity analysis for two data sets for polypropylene's production with respect to freshwater consumption

Glass Fiber

Lack of data on glass fibre production in the region where production occurs, has also made the production of glass fibre uncertain. The change in the data does not affect the GWP results, however, the impact category for the depletion of abiotic resources ADP, increased greatly when the data from German production was substituted for that from the rest of the world (figure 27).

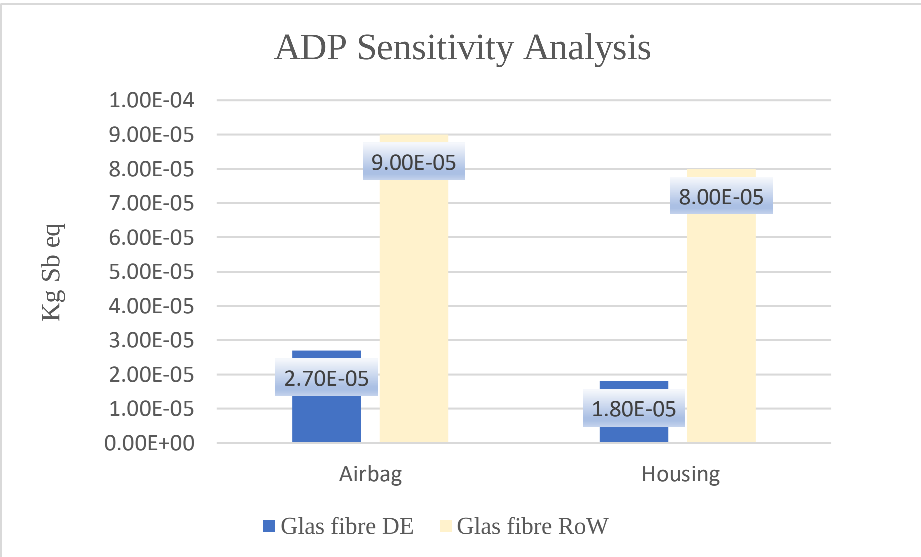

Figure 27 Sensitivity analysis for two data sets for glass fibres with respect to abiotic resources depletion

Regarding to water consumption, the airbag production increases the usage of water by 8%, and an increment by 55% for the housing's production when the data set was changed (figure 28).

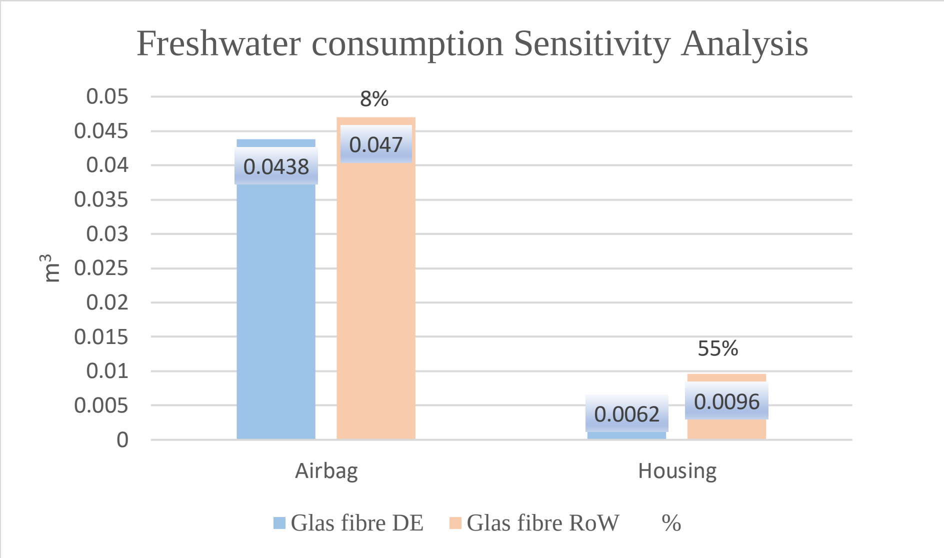

Figure 28 Sensitivity analysis for two data sets for glass fibres with respect to freshwater consumption

Based on the results of the sensitivity analysis, the climate impact results are not sensitive, the freshwater consumption results slightly vary, while the abiotic resource depletion results are highly sensitive.

Polypropylene and glass fibres are the two processes with the greatest impact on abiotic resources depletion. For the construction of the LCA model, the data sets used came from the production of glass fibers and polypropylene in Europe, although the manufacture occurs in another country outside of Europe. Given the significant differences between these two sets of data, general data sets from the rest of the world may be more relevant for modelling.

5.3 Improvements scenarios

The dominance analysis showed most significant impacts on the environment come from polyamide 6.6 and steel, both being present in large quantities in the airbags and involving significant emissions from their production processes. Different scenarios have been constructed with the objective to study the possibility to use recycled material for plastic and steel during the manufacturing of the airbag module (PAB) and see what improvements in terms of reduction of the impact to the environment can be achieved.

Scenario for recycled plastic

Several components of the airbag are manufactured from virgin plastic, which means that the plastic materials used for the manufacturing of components like the bag and the housing do not contain any recycled materials. Different percentages of recycled content (15% to 50%) for plastic materials were examined in these scenarios.

Figure 29 shows the decrease in emissions in terms of CO_2 eq. during the production of the airbag module with different recycled content of plastic. For example, it is estimated that using 30% recycled plastic in the production of the various components of the airbag module will result in a reduction of 4% in emissions, from 10,64 to 10,2 kg CO2 eq.

If further reductions in emissions are to be achieved, recycling content must exceed 50%.

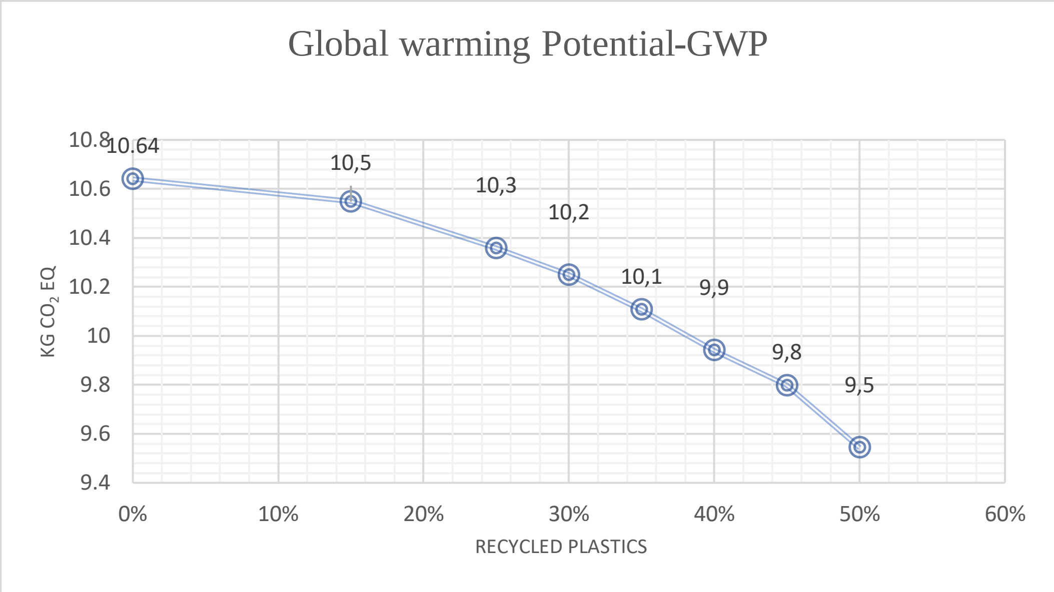

Figure 29 Scenario for recycled plastic with different recycled contend in % with respect to GWP

Figure 30 shows the slight decrease in abiotic resource depletion during the production of the airbag module when different recycled content of plastics is used in the production.

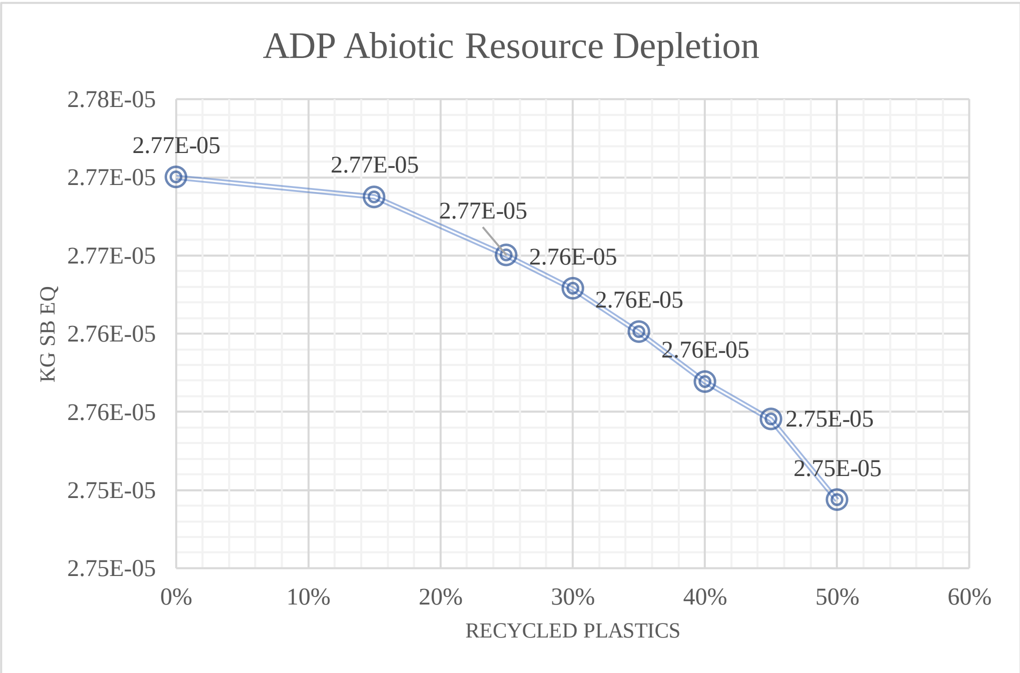

Figure 30 Scenario for recycled plastic with different recycled content in % with respect to abiotic resources depletion

In terms of abiotic resource depletion, it is not observed significant improvement, for the use of recycled plastic in different components of the airbag. It is necessary a recycled content greater than 50% to achieve an improvement of 1% in terms of ADP.

Figure 31 shows the decrease in freshwater consumption for different scenarios with different recycled content of plastic for the airbag module production

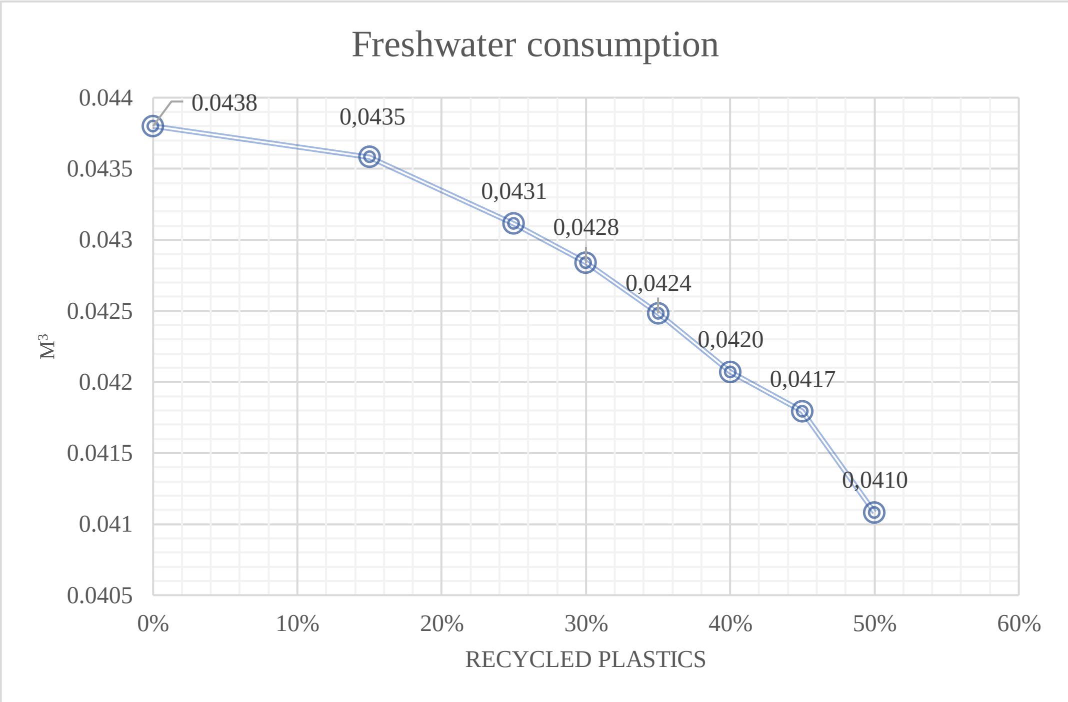

Figure 31 Scenario for recycled plastic with different recycled content in % with respect to freshwater consumption

The benefits obtained for the use of recycled content in plastic materials are also limited for freshwater consumption; for example, by using 30% recycled plastic in the airbag production, the water use drops from 43,8 liters to 42,8 litres, this is a 2% improvement in water consumption, it is necessary to utilise a material with 50% recycled content to reduce the usage of water by 6%, from 43,8 to 41 litress.

Scenario for recycled steel

For steel, different scenarios were modelled using different recycling percentages. Results show that a 70% recycled content in metal is required to achieve a 10% improvement in greenhouse gas emissions, in this case the emissions in CO_2 equivalent decrease from 10,64 Kg CO_2 eq. to 9,5 CO_2 eq. (figure 32).

Figure 32 shows different scenarios for recycled content for steel and the reduction of CO_2 eq emissions.

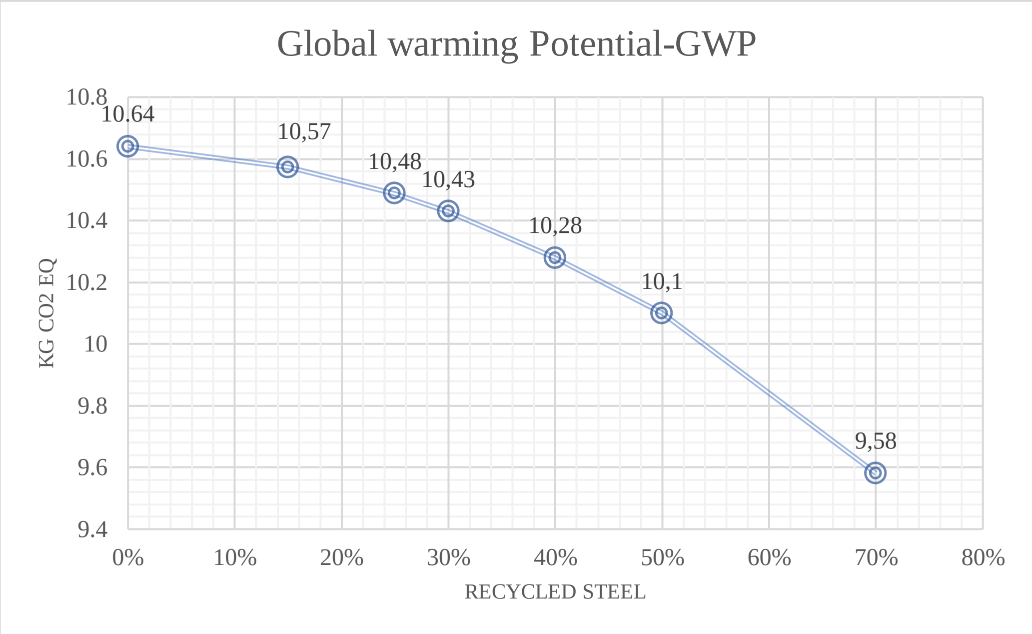

Figure 32 Scenario for recycled steel with different recycled contend in % with respect to GWP

By using 25% recycled steel and 30% recycled plastics, the company will reduce the carbon footprint of the product by 5%. The largest improvement is achieved in the manufacturing of the bag by 8% followed by the fabrication of the inflator with an improvement of 4% (figure 33).

Figure 33 shows a combine scenario with 30% recycled content plastic and 25% recycled content steel

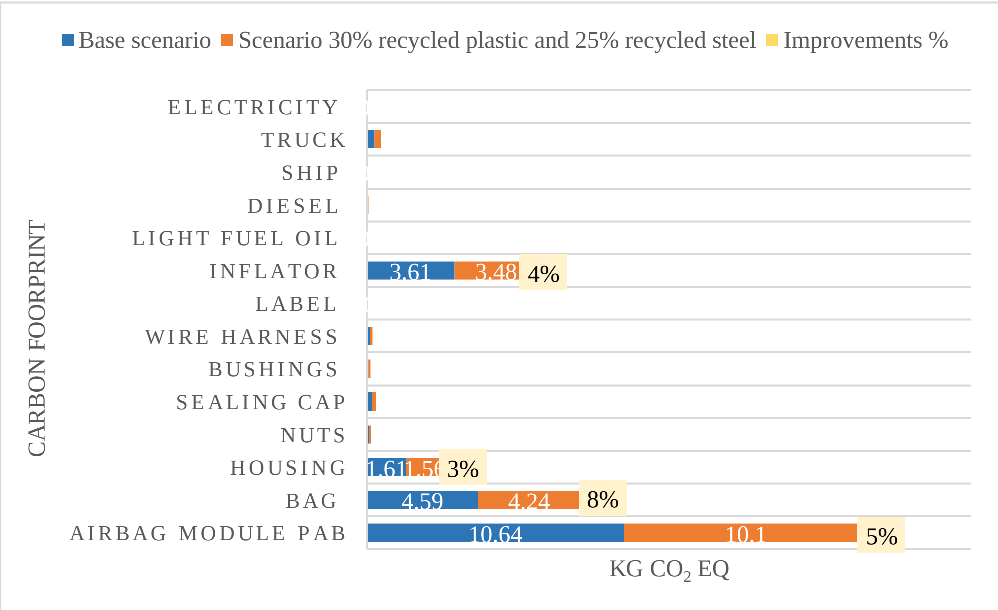

Figure 33 Carbon footprint scenario for 30% recycled plastic and 25% recycled steel in comparison with the base scenario

Scenario for alternative material

An alternative material for the manufacturing of the bag was tested in the LCA model. Following the proposal of alternative materials in the literature review, polyamide 6.6 was replaced by PET. A decrease of 21% was observed in the emissions related to the impact category "Global warming potential" for the manufacture of the airbag module (PAB) with PET material, and a decrease of 48% for the manufacturing of the bag (figure 34).

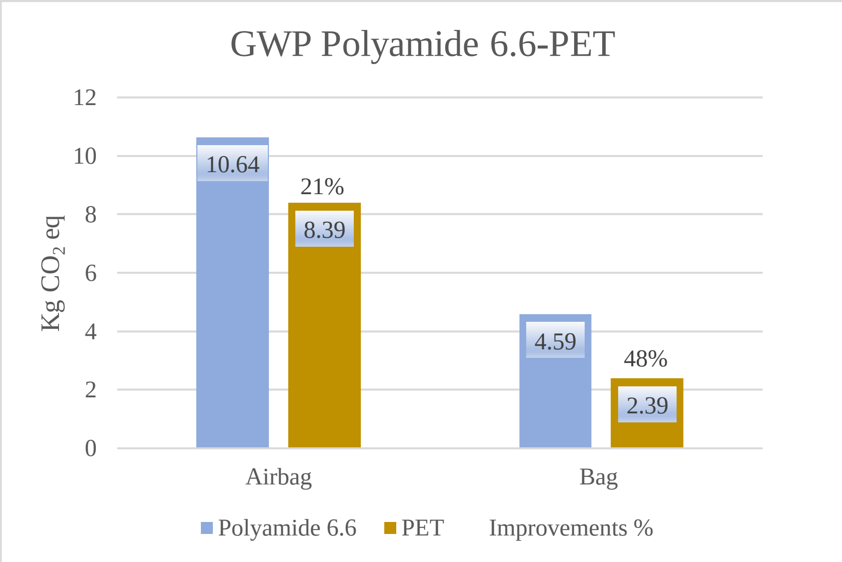

Figure 34 Comparison between polyamide 6.6 and PET for the manufacturing of the airbag and the bag with respect to GWP

Regarding Abiotic Resource Depletion (figure 35), the use of PET for the manufacture of the bag's fabric results in a 40% reduction in depletion of abiotic resources, but the total improvement for this category for the fabrication of the airbag's module is only 1%.

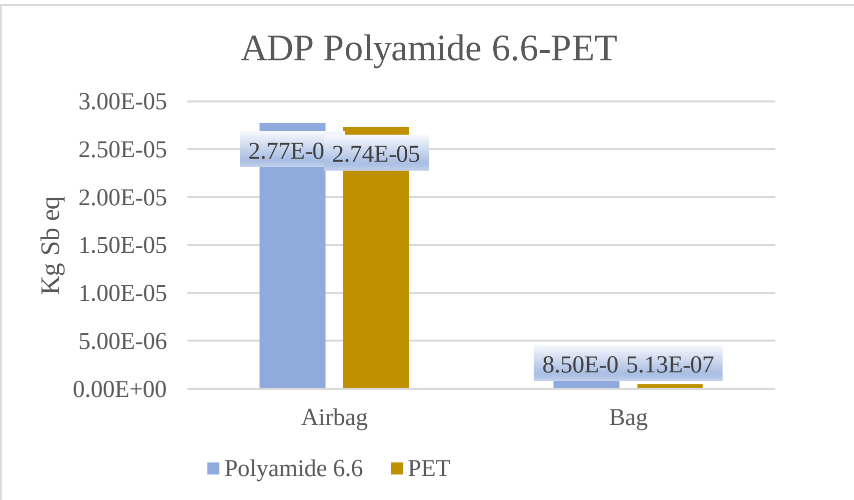

Figure 35 Comparison between polyamide 6.6 and PET for the manufacturing of the airbag and bag with respect to Abiotic resources depletion.

In terms of freshwater consumption, it has been found that using PET instead of polyamide 6.6 reduces the amount of water needed in the airbag manufacturing process by 6%. For the manufacturing of the bag the reduction is by 19%.

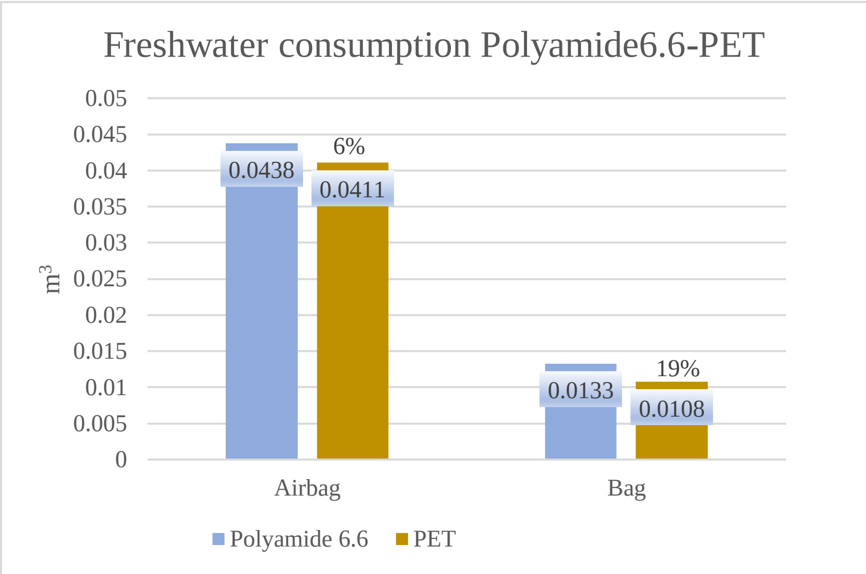

Figure 36 Comparison between polyamide 6.6 and PET for the bag manufacturing and the airbag production with respect to freshwater consumption.

According to the dominance analysis, it has been shown that polyamide 6.6 and steel have the highest environmental impact, therefore scenarios for different recycled plastics content, specifically polyamide 6.6 and polypropylene were modelled. The results reveal that the plastic materials need at least 35% recycled content to achieve a 5% improvement in terms of greenhouse gas emissions. Recycling content for plastics must be increased more than 50% if further greenhouse gas emissions reductions are required. In the case of steel, more than 50% recycled content in the metal is needed to achieve some positive improvement in the reduction of greenhouse gases emissions. It is known that steel is a material with high possibility to be recycled without losing its properties (Carbon smart, 2022) so these improvements could be achieved without compromising the properties of the components

Using recycled plastic in a variety of airbag parts does not have a significant impact on ADP depletion. The same happens with respect to freshwater consumption, it would be required more that 50% recycled content in the plastic material to achieve an improvement of 6%.

By using 25% recycled steel and 30% recycled plastics, the company will achieve a 5% reduction in the carbon footprint of its product (PAB). The low value could be due to the type of plastic used for the bag production (polyamide 6.6) and the general data set used during the modelling for the recycling process (unspecified recycled plastic), this general data maybe was not accurate for this type of plastic.

The limitation of substantial improvement in the different impact categories for plastic recycling could not be explained since it is important to investigate the recycling processes for specific plastic materials in detail and to determine what the hot spots are in these processes.

Several hypotheses may be related to these results, including the type of energy used, the type of transportation used, the addition of additional materials or chemicals required for the recycling process, etc., research in this area may exceed the scope of the thesis and require further study.

For further studies, it could be considered to replace polyamide 6.6 with other alternatives that would cause less impact to the environment, such as using PET for the bag's fabric, as proposed in different research papers reviewed in this thesis. Using PET material instead of polyamide 6.6 for bag production would be a better option according to the scenario analysis, reducing global warming potential emissions by 21%.

In addition, further investigation may be required to determine how much recycled plastic content could be used in the manufacture of the fabric's bag or housing, without compromising its properties or safety requirements.

6 Conclusion

After this LCA study it is possible to answer the research questions:

- Which part of the life cycle of the product in terms of materials, energy or manufacturing processes have a larger impact (hot spots) on carbon footprint, water use and depletion of natural resources?

It has been observed that the main hot spots during the life cycle assessment of the PAB airbag “cradle to gate” are localized in production processes like the bag, the inflator, and the housing. Materials production as plastics such as polyamide 6.6 and polypropylene have been pointed as hot spots in this LCA, other materials that present high impact to the environment were the production of steel and glass fibres.

In terms of carbon footprint, it seems that the production of plastic materials such as polyamide 6.6 and polypropylene, as well as steel production, glass fibres production has the largest impact in terms of Global warming potential. Regarding resource depletion, materials such as copper, glass fibre, seem to be the most resources demanding. For freshwater consumption, it has been observed that materials such as polyamide 6.6, steel, polypropylene, and glass fibres, are materials that require large amounts of water as well as energy use such as electricity and diesel.

- What kind of improvements is possible to make after the identification of hot spots in the sense to reduce those environmental impacts?

Focusing on the results found in this LCA study, it is possible to achieve some improvements in terms of recycling content for materials such as plastic and steel, but the greatest improvements are possible when the recycling content is higher than 50%.

Steel is a material that can be recycled without losing any of its properties, thus allowing for this type of improvement. Plastic materials can also have a higher recycling content, but in the case of components such as bags, it's important to evaluate how much recycled material can be combined with virgin material without compromising quality and safety, however this research is outside the scope of this thesis and could be aimed for further investigation.

To conclude, the final recommendation for improving the PAB's environmental performance is to begin investigating the benefits of using a percentage of recycled materials added to virgin materials during manufacturing processes. It may also be beneficial to investigate the possibility of using alternative materials in the production of components such as the bag, the inflator, and the housing, which include polyamide 6.6, polypropylene, glass fiber, and steel.

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Appendix A

Excel file designed for data collection

		Data collection for the manufacturing processes							
	Inflows								
Inflows	Raw material	Amount material required per nuts (kg)	Amount material in the final product per nuts (g)	Amount and treatment of material loss (kg)	Percentage of recycled content in the raw material (%)	Country of origin of the raw material	Biobased content (in %)	Is it possible to dismantle and recycle the material at the end of life?	Date
	Energy use during the manufacturing	Type of energy use	Amount per nuts	Unit (kWh or MJ)					
	Water use during the manufacturing	Amount per Nuts (litres)							
	Other auxilliary materials	Amount per nuts	Unit (kg or litres)						
Outflows	Outflows								
	Products	Amount per Nuts	Unit (kg or litres)	Comment					
	Waste flows								
Transportation, incoming									
	Product	typ of transportation	distance	Unit (km)	Comment				
Transportation, outgoing									
	Product	typ of transportation	distance	Unit (km)	Comment				
	Description of the manufacturing								

Appendix B

Tables with results for the impact category GWP with cut-off 1%

GWP Airbag	Kg CO_2 eq.
Airbag (PAB) complete module	10,64
Airbag-components-processes	
Bag	4,59
Inflator	3,61
Housing	1,61
Transport- truck	0,29
Sealing cap	0,19
Wire harness	0,12
Nuts	0,09
Bushings	0,08

Tables with the results (GWP) for airbag's components regarding to GWP

GWP- Bag	Kg CO_2 eq.
Bag manufacturing	4,591
Bag's components-processes	
Polyamide 6.6	4,11
PET	0,17
Transport Truck	0,06
Electricity	0,22

GWP Inflator	Kg CO_2 eq.
Inflator manufacturing	3,61
Inflator's components-processes	
Steel	3,08
Polyamide 6.6	0,02
Pyrothecnics	0,05
Trasnport-Truck	0,14
Electricity	0,26
Silicone	0,02

GWP Housing	Kg CO_2 eq.
Housing' production	1,6
Materials, energy and transportation	
Polypropylene	0,8
Glass fibres	0,3
Transport-Truck	0,05
Transport-ship	0,01

Tables with results for the impact category **ADP** with cut-off 1%

ADP Airbag	Kg Sb eq.
Airbag (PAB) complete module	2,77E-05
Components	
Housing	1,85E-05
Wire harness	6,73E-06
Inflator	1,53E-06
Bag	8,50E-07

Tables with the results (ADP) for airbag's components that require high amount of natural resources

ADP Housing	Kg Sb eq.
Housing's production	1,85E-05
Materials, energy and transportation	
Glass fibres	1,81E-05
Polypropylene	2,09E-07
Electricity	1,92E-07

ADP Wire harness	Kg Sb eq.
Wire harness (complete module)	6,70E-06
Materials, energy and transportation	
Copper	6,50E-06
Polyvinylchloride	1,60E-07
PET	6,90E-08

ADP Inflator	Kg Sb eq.
Inflator (complete module)	1,53E-06
Materials, energy and transportation	
Steel	9,16E-07
Silicone	4,58E-07
Electricity	1,14E-07
Diesel	1,55E-08
Gases	9,84E-09
Polyamide 6	8,01E-09

Tables with results for the impact category **Freshwater consumption** with cut-off 1%

Freshwater consumption Airbag	m^3
Airbag module (PAB)	0,0438
Materials, energy and transportation	
Inflator	0,021
Bag	0,013
Housing	0,006
Wire harness	0,001
Nuts	0,0006
Sealing cap	0,0005
Bushings	0,0005
Diesel mix	0,0003

Tables with results for Freshwater consumption for airbag's component that require large amount of water

Freshwater consumption Inflator	m^3
Inflator's production	0,021
Materials, Energy and transportation	
Steel	0,019
Electricity	0,001
Process water	0,0002
Silicone	0,0002
Diesel	0,0001

Freshwater consumption-Bag	**m^3**
Bag's production	0,013
Materials, Energy and transportation	
Polyamide 6.6	0,010
Electricity	0,002
PET	0,0007

Freshwater consumption- Housing	**m^3**
Housing's production	0,006
Materials, Energy and transportation	
Polypropylene	0,003
Electricity	0,0016
Glass fibres	0,0011
Diesel	4,9E-05

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