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Life Cycle Assessment on Autoliv's Driver Airbag

Master of Science Thesis in Environmental System Analysis

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The picture of airbags in a car (used with written permission)
Sources: http://www.sacarfan.co.za/2009/05/volkswagen-golf-vi-arrives-in-south-africa/

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Abstract

This master's thesis is an evaluation of the environmental performance of a driver airbag, produced by Autoliv Sverige AB, by using cradle-to-grave Life Cycle Assessment methodology. The studied airbag is a pyrotechnical airbag, thus representing 80% of types of airbag produced by Autoliv. Pyrotechnical airbags operate solely by the deployment of chemical mixtures, as opposed to hybrid airbags which also used compressed nitrogen. The study includes data collection by surveying the companies throughout the supply chain and conducting literature review for general data to supplement the site-specific data; calculating the environmental parameters; analyzing the results by locating dominant substances and processes; and comparing the environmental load of the airbag package with a complete car.

The results of this LCA study shows that life cycle of one unit driver airbag may cause global warming equivalent to 31.78 kg of CO_2, acidification equivalent to 50.42 g of SO_2, eutrophication equivalent to 39.35 g of NO_x, resource depletion of 1.52E-10 g/reservebase, toxicological impact to aquatic equivalents to 947.73 m^3 of water, and 67.78 g of contaminated bodyweight for human toxicity. The entire life cycle for one airbag also generates 4.93 kg waste and consumes 569.56 MJ energy and 79.24 kg water. Dominant processes in the whole life cycle are steel production due to its high water and energy consumption, polyamide production due to its high energy consumption and various emissions, and the use phase due to its high fuel consumption.

Some materials in the airbag system should be avoided for environmental consideration, mainly by reducing the weight of steel components and polyamide content in airbag module. In particular, zinc coating, used in steel production, is associated with a relatively large environmental loads. Further research should be directed to more finely detect areas of improvement with regard to weight reduction and raw material selection.

1. Introduction

1.1. Background

The transport sector has long been the object of environmental concerns for two reasons: it is an energy intensive sector, and thus generates a substantial amount of emissions. Within the European Union, the transport sector is the largest consumer of oil products: it accounts for almost 60% of total delivery in 2007 and is expected to consume even more in the few years to come. (European Commission, 2008) Energy consumption of the transport sector in the region amounted to 370.4 million tonnes of oil equivalent (toe) in 2006, or almost one third of total energy consumption (Figure 1). (Eurostat, 2009)

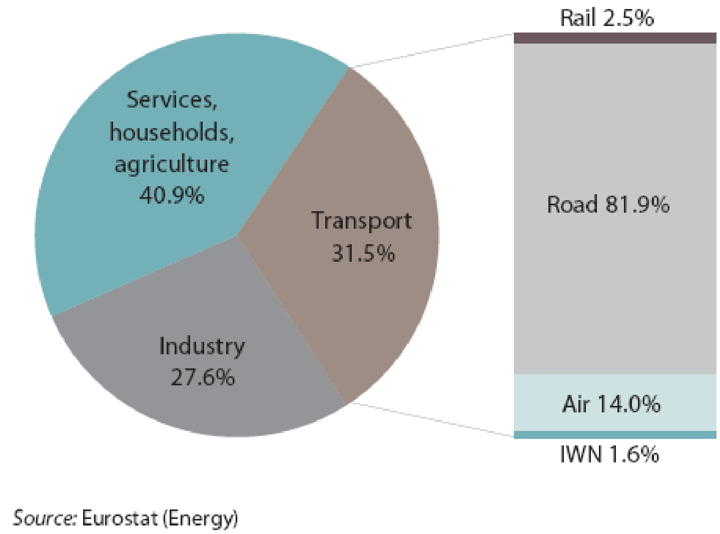


Figure 1. Share of Transport in Final Energy Consumption, EU-27, 2006 (%TOE)

Environmental impacts associated to a car's life cycle start with resource and energy use for its raw material extraction, which contributes 23% of the total car environmental impacts (Subic, 2006). While in use phase, the important contribution is its greenhouse gas emissions. In European Union, fuel combustion in transport came in third place with 19% after energy industries and manufacturing industries sectors (EEA, 2008). Moreover, End of Life Vehicles (ELV) contribute to approximately 1% of the total waste in Europe. (European Commission, 2003)

The automotive industry has applied Life Cycle Assessments (LCAs) for a long time. (Schmidt, 2004) The main focuses are to increase the understanding of life cycle implications for different car designs, and to explore technology options in renewable fuels. Some good examples of LCA studies are: analysis of the use of catalytic converters in cars (Amatayakul, 2000), the excess of magnesium in reducing car weight (Tharumarajah, 2006), the environmental impacts of composite materials used to reduce car weight (Duflou, 2009), and greenhouse gas emissions of several types of fuels for road transportation in China (Yan, 2009).

The European Union has proposed three strategies to reduce environmental impacts for the transport sector, namely the improvement of engine efficiency, the use of alternative fuels and the reduction of vehicle weight (Helms, 2007). Therefore, the trend in automotive industry today, particularly in Europe, is toward smaller-size cars (Autoliv, 2008) such as Volvo C30, Renault Megane, Volkswagen Golf, Honda Jazz, and Peugeot 306. However, small cars have a safety level of two times lower than cars in general (Wood, 1995).

Autoliv as the worldwide leader in automotive safety products is devoted to align its product development to the same principle. Autoliv recently conducts a project to investigate the environmental impacts of their products by means of LCA methodology. This thesis has been performed on behalf of Autoliv Development AB, focusing on Driver Airbag Module (ADPS-1.XA) produced by Autoliv Sverige AB. Other on-going LCA studies in Autoliv are for seatbelt, electronic control unit, and night vision camera.

1.2. Purpose

The goal of this study is to investigate the environmental performance of Autoliv's airbags from cradle to grave. The results of the study should help in the identification of improvement possibilities and further can be used as a basis of reference for future product development research. More specific purpose of this study can be found in Chapter 4 (Goal and Scope Definition).

1.3. Method and Delimitation

In order to investigate the environmental performance of Autoliv's Airbag, an LCA study is used. This study deals with the life cycle, from cradle to grave, of the driver airbag module. Use of natural resources, transportation, energy consumption, waste and emissions to air and water are considered. In the study the production of materials and component manufacturing takes place worldwide. The assembling plant for airbag module is located in Vårgårda, Sweden, but the products are sold worldwide together with the car. End of life of car is considered according to the scenario commonly performed in this current time. The road transportation in this study was assumed to use long distance truck with Euro 2 standard (or equivalents) to represent the normal situation of transportation vehicle.

This study was done together as a team, but specifically Setyo focused on collecting site-specific data from the suppliers and calculations for the inflator part, while Arief focused on gathering average life cycle inventory data and calculations of other components (label, nut, cushion, can and cover). Finally, the authors worked together in writing the report.

2. The Company and the Product

2.1. Autoliv

Autoliv is the worldwide leader in automotive safety and was among the first to introduce high-tech products like seatbelts and airbags to the market. During the past 50 years, the company has emerged from a small Swedish family business to a global corporation with more than 80 facilities in 32 vehicle producing countries. Today Autoliv employs 36 000 associates, whereof 4000 are in research and development, with annual sales of US $6.8 billion in 2008, and makes vehicle safety equipment for all major automotive manufacturers worldwide (Figure 2). Autoliv Development AB is the Swedish research company of the corporation in Vårgårda facility, Sweden, and is responsible for the LCA studies.

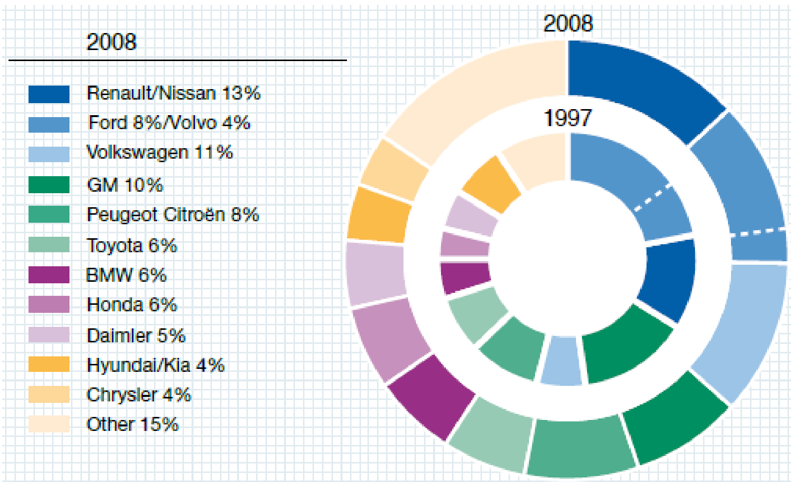


Figure 2. Customers of Autoliv Products
Source: Autoliv Annual Report 2008

Autoliv produces a wide range of automotive safety equipment products such as seatbelt systems, steering and airbags (i.e. airbag for the driver, front passenger, side curtain, and knee), electronics equipment (such as electronic control units, and satellite sensors), and accident-prevention systems (such as safety cameras, radar systems, and night vision system).

2.2. Airbag in General

Airbag is one type of automotive safety equipment composed of a flexible bag designed to rapidly inflate in case of accident to avoid passengers' collision with the steering wheel or window. Airbag has helped save lives and reduce injuries on the head (Figure 3). In addition, the number of deaths suffered by drivers using seat belts and airbags has decreased 26% compared to the use of a seatbelt only (Casiday, 2000).

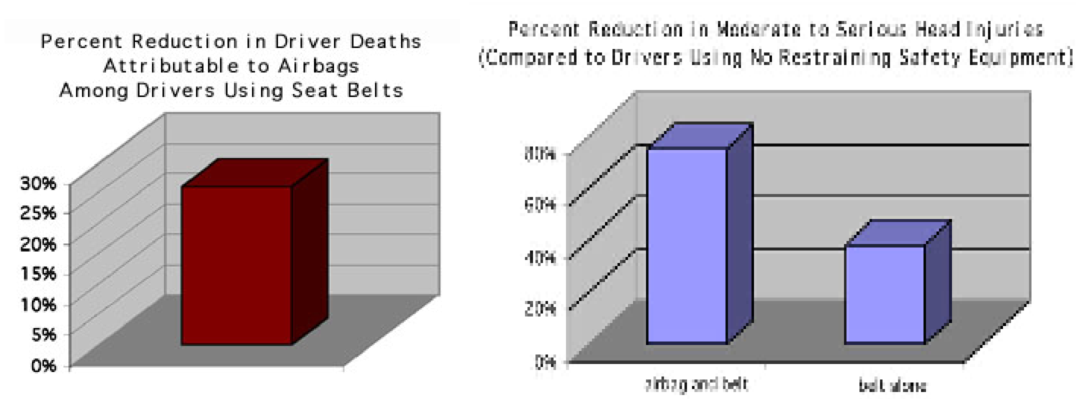


Figure 3. Benefit of Airbag Use in Driving Safety
Source: http://www.chemistry.wustl.edu/~edudev/LabTutorials/Airbags/s.html

The airbag works to protect the rider starts from the time of the accident (Figure 4). At this time the sensors will send signals to the Airbag Control Unit (ACU). The signals from ACU will turn on the initiator with electrical impulses and produce high temperatures to make gas generant explode. The resulting nitrogen gas makes airbag inflate. As the riders hit the sack, the gas will come out in controlled amount through small vent on the bag. (Casiday, 2000)

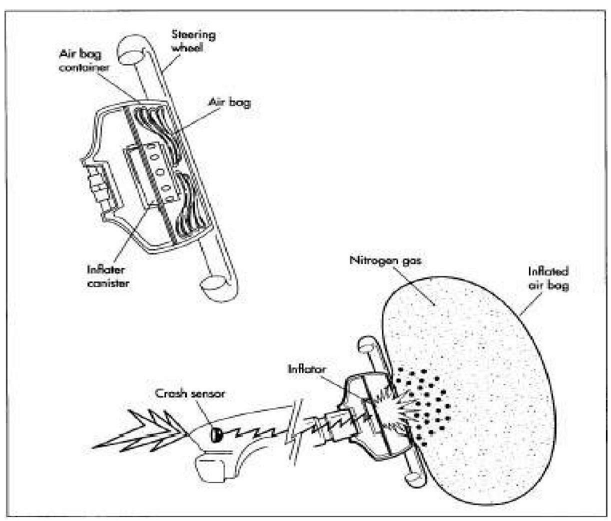


Figure 4. Driver Airbag Deployment
Source: http://www.swicofil.com/airbags.html

2.3. The Driver Airbag Module

The airbag module considered in this study is an Assembly Module for Volvo – P14 with part number 608178000A. This studied airbag represent 80% of types of airbag produced by Autoliv and can provide variable occupant protection based on severity of impact. The total weight of driver airbag module is 1.56 kg and consists of six main components, namely label, nut, cushion, can, cover and inflator. The weight and material data for the Assy Module, Volvo–P14 was determined on the basis of the Autoliv internal documentation of the components used in the airbag, i.e., Product

Lifecycle Management (PLM). The resulting material composition of the studied airbag module is shown in Figure 5.

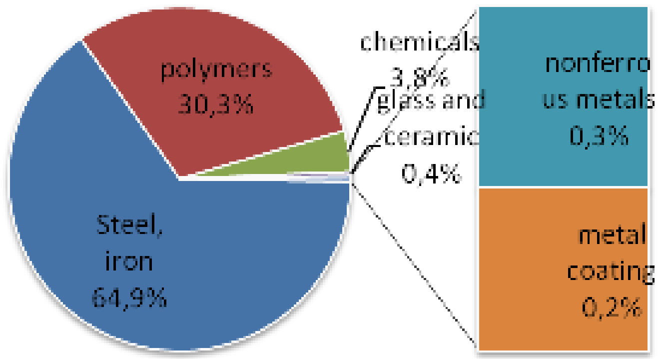


Figure 5. Material Composition of A Driver Airbag Module (in % of mass)

There are many different types of material in each of material category. Each of different materials has different role in airbag system. The list of main material used in airbag module are presented in Table 1 below. The details can be seen in Appendix.

Table 1. Material Summary for One Driver Airbag Module

Material	Amount (gram)	Types	Role in airbag module
Steel	1017.3930	Carbon steel Stainless steel Iron steel	- Stud, tube, screen, adapter - Base, initiator - Nut, diffuser
Polymers	475.5750	ABS Polyamide 6.6 EPDM PET PMMA Polyethylene Polypropylene	- Insider part of cover - Cushion, thread - leather surface for cover - Shunt ring, label - Emblem - Label for airbag module - Label for cushion
Chemicals	59.9010	Guanidine nitrate Copper nitrate Potassium nitrate Ink	- Gas generant - Igniter - Label
Ceramic and glass	6.4360	Ceramic paper Sealing glass	- Filter inside inflator - Sealing inside initiator
Non-ferrous metal	4.3660	Aluminum alloy Platinum Nickel alloy	- Emblem, inflator, igniter tube - Bridgewire - Initiator
Coating	3.9108	Zinc coating Nickel coating Gold coating	- Coating for the can, pinne, stud - Coating for initiator - Coating for initiator

3. Theoretical Framework

3.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is a technique that can be used to assess the environmental impact and potential of a product, process or service from the entire life cycle (Figure 6), by the following steps:

a. Compiling the use of energy, raw materials and environmental emission associated with the product, known as inventory analysis phase.
b. Evaluating the potential environmental impacts caused by the use of raw materials, energy and environmental pollution that has collected in phase 1, known as impact assessment phase.
c. Interpreting the results obtained from phase 2 to obtain the information required in accordance with the objectives of the LCA study of LCA, known as interpretation phase.

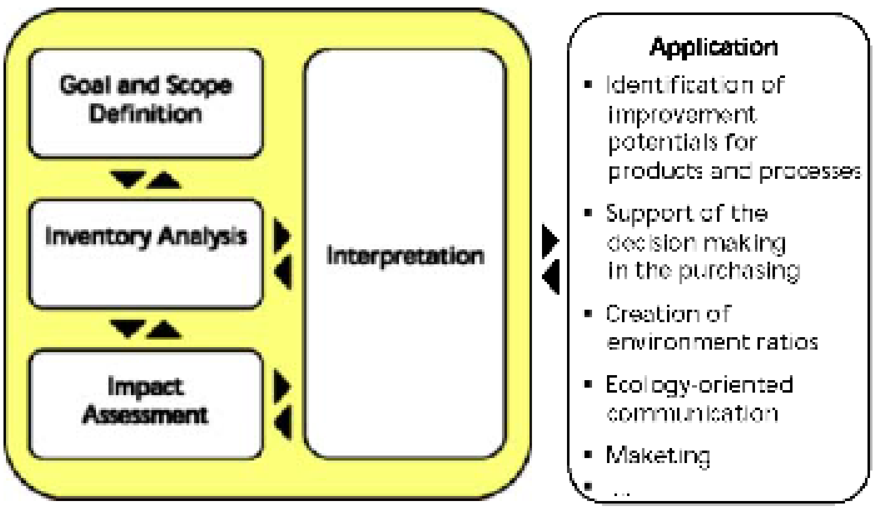


Figure 6. Three Main Steps in An LCA Study
Source: Tillman, 2008

According to Baumann & Tillman (2004), there are several reasons why LCA has become an established method in the environmental analysis circle. The scope of LCA studies cover the whole process starting from the retrieval of raw material, energy consumption, generated wastes and emissions during the making of the products, product use and disposal of the product. In selection between choices, LCA study can help decision makers compare the environmental impacts caused by each alternative and the decision making process will be more objective and comprehensive. LCA can also be used to locate the stage of the process that contributes to the greatest environmental impact of the overall product life cycle, something often referred to as hot spot identification.

In addition, by using LCA, it is also possible to identify the changes in environmental impacts caused by process change, both for retrospective or prospective. Furthermore, the LCA result can be used as basis of information for environmental improvement plans in the future. At the same time, it serves as a quick way to learn the processes, materials and systems life cycle of a product. LCA could also be used as a basis for further decision making with additional technical approach, social and economic (Miettinen, 1997).

Environmental issues will be more complex ahead, even though end-of-pipe technology to reduce emissions from the source growing rapidly (Lindfors, 1995). Therefore, in order to prevent environmental damage, the current paradigm shift is needed from the end-of-pipe into the paradigm of doing business and comprehensive preventive (Pesso, 1993) and LCA is one of the approach used to help in directing towards sustainable development (UNEP, 1996).

Various types of LCA have been increasingly developed along with the use of LCA in various applications, starting from conducting a complete LCA study and detail to the use of simple LCA as rule of thumb. Moreover, life cycle thinking is increasingly applied in policy making, including in private companies considering their production activities, without necessarily conducting a real LCA study.

LCA can help decision makers to learn the entire system of a product and to be able to avoid the occurrence of sub-optimization that can happen if only one step processes are studied (Curran, 2006). An example is the use of catalytic converters. The installation gives benefits in the use phase, but based on an LCA study conducted by Amatanyakul (2000) catalytic converter produces greater environmental impacts on the phase of raw materials extraction. This is the advantage that the study did take the perspective of the whole system.

Great interest to study LCA can be explained by seeing a paradigm shift in environmental work, particularly in industry, not only to use strategies of end-of-pipe, where the waste is processed only after the formation of waste or with emission control strategies, but using the whole life cycle approach (life cycle thinking). The paradigm is considered more effective in improving the environment, particularly for industrial products that create more pollution during the use phase and the time they become a waste. It has been applied in several countries in Europe and in the United States as a government policy for environmental management. In addition, LCA is also a study of methods of quantitative data and therefore is more objective.

In addition, LCA study may involve more than one environmental issue in the process of structured study. At the same time, as more results of LCA studies conducted and published, there will be more and more of the available environmental data and this will facilitate other LCA studies. Some projects such as the Society for the Promotion of Life Cycle Development (SPOLD) was formed in 1992 with the primary purpose of providing inventory data for LCA study results public (Hindle, 1996). There are also other initiatives such as the Product Ecology Project, the Society of Environmental Toxicology and Chemistry (SETAC), European Commission for Ecolabelling (Udo de Haes, 1994), and the Center for Environmental Assessment of Products and Materials

(CPM) in Sweden. In addition, there have been many softwares developed with the aim to facilitate the LCA study and its use, such as Gabi and Simapro.

Methodology of Life Cycle Assessment (LCA) briefly covers three main stages, the goal and scope definition, inventory analysis and impact assessment. These will be explained further below.

3.2. Goal and Scope Definition

Defining the purpose of the study include the identification of purpose of the study, the reasons for the implementation of LCA study and the intended user to be communicated. Goal and scope definition include the following (Baumann & Tillman, 2004):

1. Functional Unit, which will be used as a reference unit of all data.
2. System limitation, i.e., part of the system to be included into the system analyzed.
3. Types of environmental impacts to be considered, this parameter will determine the choice of data to be collected in the inventory analysis.
4. Depth of the study, this set of data requirements that will be used.
5. Necessity of critical review and type of reviews that will be conducted.

3.2.1. Functional Unit

LCA is a quantitative method therefore the function must be expressed in quantitative terms. Normalization of figures across the diverse processes is done by defining the functional unit. Definition and selection of functional unit is one of the most essential parts in this phase. Functional unit explains the function, benefit and performance of the studied product. In addition, the functional unit serves as the basis of evaluation and comparison of alternatives to be studied. Defined functional unit should be clear, measurable and relevant to the input and output data (Baumann & Tillman, 2004).

3.2.2. System Boundary

To be able to give an assessment of environmental impacts of a process objectively, there are some points that must be defined and limited. Environmental impacts of the same process may vary depending on many parameters. Therefore the system boundaries in a study must be determined.

Boundary of natural systems
The beginning of a product life cycle is start from the extraction of raw materials from natural systems. But sometimes it is very difficult to determine the boundary between the technical systems being studied with natural systems. This is important, considering the environmental impact will determine what will be included in the analysis of inventory and for subsequent inclusion in the impact assessment.

Geographic Boundary

In the globalized world economy, the materials of a product as sophisticated as an airbag would come from different regions in the world. This raises the issue of site specification, since different regions have different infrastructure make-out, such as fuel types for electricity generation and modes of transportation. As an illustration, electricity in Sweden mostly comes from hydropower and nuclear power plants. Therefore emissions in Sweden will be clearly different from emissions for e.g. electricity generation in Germany, where almost half of the amount of electricity is generated by burning coal. (IEA, 2008) Therefore, if the area of the product life cycle is not specified, it could have different consequences for the results.

Selection of geographic boundaries in a LCA study also determines the type of data to be used, since there are site specific data and general data. If general data are used, there should be a qualitative description of geographical areas that can still be represented by them. This selection is determined by the background of the LCA study. This background could be to study the environmental impacts of a product or used to compare differences between processes. It will also determine the use of marginal data or average data. Marginal data would be better used in LCA projects which studies the changes in production, because it usually gives an impact on margins. If the average data is used, there are other things to consider, such as what type of data can have the average statistical figures.

Time Boundary

Time boundary is principally influenced by the purpose of the LCA study. If the goal was to evaluate the environmental impact caused by a product, then this can be answered by LCA with the type of accounting, which is retrospective (backward time orientation). If the purpose of the LCA study is to investigate impact of the changes will be made on the future of materials or processes in the life cycle of a product, it would be better if you use the LCA-oriented changes (change-oriented), because it is prospective (forward time orientation).

Application of LCA results depending on the time period that can be represented by the data collected. For example, if a production process had been changed, it's important to know the scope of data collected in the LCA study is based on the production before or after the change is accomplished. In addition, several categories of environmental impacts or the method for calculating the potential environmental impacts are calculated using the time base, such as global warming potential (global warming potential) and ozone depletion potential (ozone depletion potential).

Boundary of technical systems

Cut-off criteria

While doing LCA studies, sometime a decision to cut the life cycle of product must be made (not following the cycle to more processes upstream or downstream). The cutting must be based on the assumption that the contribution to the environmental impact of the exclusion process can be negligible compared with the life cycle of studied technical systems. The decision to cut the life cycle in change-oriented LCA study should be based on what is relevant it means to consider the processes that are affected by these changes. The process that is not giving any affect should be excluded from the technical system. Many LCA studies often conducted from cradle to grave, but it can be also studying from cradle-to-gate, gate-to-gate or gate-to-grave. This shows the existence of cutting off the LCA.

Allocation

LCA studies often find situations where several different products are made in the same process. If environmental impacts should be expressed in terms of one product, it would appear that the problem needs to be allocated. There are three basic cases in which the allocation problem will certainly happen (Baumann & Tillman, 2004):

1. Processes with several different products
2. Waste treatment processes with inputs from several different products
3. Process with a recycling circle, when a product is recycled into other products.

Allocation can be avoided by increasing the level of detail of modeled system, but can also be managed through system expansion. If the allocation can not be avoided, then the environmental impacts can be broken down according to the functions of the existing system. One of basis to break the environmental impact is by physical connection. If it is difficult to use, another connections like economic linkages between the products are available (Baumann & Tillman, 2004). Attention should be given when using the allocation since differences in results could be caused by the use of different basis in doing allocation.

3.3. Inventory Analysis

Inventory analysis is the second step of the three main steps of LCA. In this second step, a model of which represent the studied system is built in accordance with the boundaries that have defined at goal and scope definition. This model describes a not completed mass and energy balance of the system, and only considering flow of mass and energy that are relevant to environment. Things that should be done in the inventory analysis step are as follows (Baumann & Tillman, 2004):

1. Construction of flow model in accordance to system boundary - flow models are usually documented as a drawing showing the flow of processes belonging to the analyzed system and products that flow between these activities.
2. The collection of data for all processes included in the analyzed system - data collected includes all flow in and out of all activities, consist of raw materials, energy in its various forms, products, and solid waste, pollution and emissions to air, soil and water.
3. Calculation of environmental load of the system based on the functional units.

3.4. Life Cycle Impact Assessment

Environmental impact assessment is the third phase of Life Cycle Assessment methodology. This step aims to explain how big the impact of environmental burden that has been collected and counted in the inventory analysis. Another goal is directed to incorporate the information obtained from the inventory analysis into the parameters of a more compact, making them easier to interpret. This is done by doing the classification, characterization, and then weighting.

3.4.1. Classification

Classification means sorting the collected parameters (emissions, energy, amounts and types of raw materials) obtained from the inventory analysis in accordance with the type of environmental impact caused by these parameters. Emissions are then grouped into several categories. One emission can be entered into various types of categories. For example, NO_x is classified into both acidification and eutrophication.

Global warming
Over the year's emissions from industries, car, fuel combustion, deforestation has led to the phenomena called as the global warming. This is caused due to the greenhouse effect. Gases as carbon dioxide, NO_x, SO_x and methane cause the heat to be trapped within the earth and stop it from moving into the space. This has led to increased temperature of earth and has led to climate change.

Acidification
Acidification is another process where SO_x, ammonia and NO_x are produced due to combustion of fuel and other processes that may result in acid rain (fog, smog) on reaction with water vapors on the air. These results in acidification, which is a threat to fresh water organisms and marine life since the water will become acid. It also has negative impacts on like rivers, lakes and forests. Acidification potentials are often expressed as SO_2 equivalents.

Eutrophication
Eutrophication associated with the increasing nutrients in an excess way and lead change of particular species composition and increased biological productivity, e.g., blooming of alga or other biomass in a water basin. In further condition, eutrophication leads to increasing oxygen consumption caused by the increasing decomposition of biomass. Eutrophication potentials are often expressed as PO_4^{3-} equivalents (Baumann & Tillman, 2004).

Aquatic ecotoxicity
The basis for the identification of hazard to the aquatic environment for a substance is the aquatic toxicity of that substance. Classification is predicated on having toxicity data for fish, algae or other aquatic plant available. These kinds of organisms are generally accepted as representative of aquatic fauna and flora for hazard identification. Data on these particular organisms are more likely to be found because of this general acceptance by regulatory authorities and the chemical industry. The characterized environmental releases for example are arsenic, cadmium, chromium (III) and lead. The ecotoxicity in aquatic are often expressed as m^3 polluted water equivalents.

Human toxicity
The human toxicity potential are a calculated index that reflects the potential harm of a unit of chemical released into the environment, is based on both the inherent toxicity of compound and its potential dose to human. The compounds released to air like cyanide, arsenic, cadmium, dioxin, nickel, polyaromatic hydrocarbon and mercury are classified to cause toxic affect to human. Total emissions can be evaluated in terms gram contaminated bodyweight equivalents.

Resource depletion
Reserve-based resource depletion is defined as the part of an identified resource that meets minimum physical and chemical criteria to current mining and production practices. Only resources, whose depletion is judged to become, or still be, a problem within the next one hundred years is considered in the characterization method. (Lindfors et al., 1995) As this LCA takes into consideration the all raw material and energy consumption like crude oil, coal, bauxite, iron, etc. over the life of the airbag therefore it is important to study the impacts on natural resource depletion.

3.4.2. Characterization

Characterization is a process in which a quantitative assessment of contribution for each parameters according to their respective category and then aggregated. Characterization is based on scientific analysis that shows a causal relationship in natural system, so it is objective. However, impact category selection and characterization methods are subjective in accordance with the existing boundary on the goal and scope definition.

3.4.3. Weighting

Weighting means summation and comparing the results of characterization of all environmental impact categories. It can be done by using one or several weighting methods available today. The methods basically explain how people think in assessing the results of the inventory analysis or the results of characterization. Weighting which in this case objectively, but the selection of weighting methods can be subjective (Baumann & Tillman, 2004). Basis for weighting factors can be:

a. *Monetarization* - assessment is described as the estimated amount of money can compensate for the damage to the environment or the price of the system of specific environmental carrying capacity. This price can be derived from the opinions of individual's willingness to pay.
b. *Written target* - The difference between the current existing conditions of contamination with the desired target can also be used as the basis for a weighting factor.
c. *Competent panel* - The panel that can give consideration to weighting factors. Panel may consist of scientists, decision makers in a company or government, and others.

Since the basis for a different weighting factor between several existing methods above, then would be produce different conclusions on the same study. This is one reason why the need to use more than one method of weighting for a LCA study. Classification and characterization step of the LCA are two things that must be done according to the ISO, while the weighting are optional (ISO/CD 14042, 1999).

4. Goal and Scope Definition

4.1. Goal of the Study

The goal of this study is to investigate the environmental performance of Autoliv's airbag, from cradle to grave. The application of the results should help in the identification of improvement possibilities and further can be used as a basis of reference for future product development research. The intended audience for this study is mainly Autoliv Development AB and Autoliv Sverige. The LCA is critically reviewed by the supervisors at Chalmers and Autoliv as well as by the examiner at the Department of Environmental System Analysis, Chalmers.

The purposes of this LCA study are as follows:

1. To identify the environmental impacts that can be associated with the airbag.
2. To analyze several environmental impacts such as consumption of different resources, e.g. energy, water, materials, etc., emissions of specific pollutants such as CO_2, NO_x, SO_2, etc. and amount of generated wastes.
3. To determine the relative environmental load of the airbag package compared to a complete car.
4. To determine whether there are materials in the product that should be avoided for environmental reasons.

4.2. Scope of the Study

4.2.1. Product Definition

The studied product is Autoliv's pyrotechnic driver airbag module produced by Autoliv Sverige AB in Vårgårda, Sweden. The specific part number is 608178000A. The module belongs to the pyrotechnical airbag family. The reasons for choosing the particular airbag module as studied product of this LCA study are:

a. The airbag family represents about 80% of the airbag product produced by Autoliv worldwide.
b. The family is sold to more than one customer.
c. The family is based on the currently common technology in airbag.
d. The module has generally cooperative and traceable suppliers and customers, as attested by the contact at Autoliv's research center.

The product does not include the sensor, cables and the electronic control unit, which also constitute the whole airbag safety system. The six components of the airbag module are assembled together in Vårgårda, but manufactured and transported from other sites. The components are shown in Figure 7 and consist of:

- Label
- Nut
- Cushion
- Can
- Cover
- Inflator

Figure 7. Components of Driver Airbag Module

4.2.2. Functional Unit

The functional unit of this study is one pyrotechnic driver airbag module as it is sold to customers. Being a driver airbag, the module includes a part of the steering wheel, the cover, which will break open during airbag deployment.

4.2.3. System Boundaries

Natural boundary
The cradle for this study is raw material extraction for each of the airbag module's component. Steel as the main raw material is mostly manufactured from metal scrap, but in some cases it comes from ore. The polymer is manufactured from crude oil.

The airbag use phase follows the car natural boundary in which emits many gases to the air. The end of life considers the landfilling and waste incineration of waste, while the recycled metal and other material was excluded from the study.

Geographical boundary
The airbag is manufactured by Autoliv Sverige AB at Vårgårda assembling plant, Sweden. Airbag components were manufactured in European region, except for the nut where produced in Taiwan. The can and label is produced in Sweden, while the cover was manufactured in Germany. The cushion was manufactured in Portugal, while the inflator was manufactured in Romania. The product was sold to Volvo Cars Ghent in Belgium, and installed in Volvo C30 cars that are distributed and sold worldwide.

Time boundary
Almost all of the collected site specific data are based on the production in the year 2009 and small portion of it is based on the production in 2008. The average data that was used was checked in advance to match the time relevancy, and most of them are still within the time constraint.

Boundaries within the technical system
The production infrastructure, maintenance and capital goods as well as personnel-related environmental impact are excluded in this study. The car manufacturing processes included in this study is only the installation process in which only the related phase when the airbag installed into the car. The study will use the assumption of car use phase and end of life since assumed as the same with the use phase and end of life for the airbag. This assumption was made based on statement by Volvo environmental department personnel. (Volvo, 2009)

The allocation methods in this study vary between activities but the weight and economic value were the most commonly used. Economic value-based allocation method was used to assign electricity consumption needed to manufacture the airbag components between all products manufactured by suppliers.

The airbag and its components are transported using a returnable box, i.e., if it is empty the box is returned to the supplier of the transported product. This transportation box was not included in this study. It is assumed are no loss during all transportation processes.

4.2.4. Choice of Environmental Parameters

Environmental parameters that describe the use of resources, energy, generating waste and emissions to air and water are included in this study.

4.2.5. Choice of Methods for Aggregation and Evaluation

The chosen environmental impacts categories that were used in LCIA are:

- Global warming (100 years)
- Acidification (max)
- Eutrophication (max)
- Ecotoxicity, aquatic
- Human toxicity, air
- Resource depletion (reserve based)

The characterization methods and indices are taken from the CIT Ekologik index list (May 2000). The environmental impacts were chosen through discussion with Autoliv as the intended audience of this study.

4.2.6. Requirement on Data Quality

Raw material acquisition data as far as possible are traced to the suppliers. But, if it is not possible, the average data were used. The average data mostly collected from Chalmers CPM LCI databases and European Life Cycle Databases (ELCD). A small portion of the average data was also collected from US LCI Databases, especially for gas generant production in which are produced in US. The average data concerning raw material extraction for each of the component were represents the European average data. Except for the nut in which was produced in Taiwan, it use global average data for steel production

Most of the manufacturing data used in this study is first hand quantitative data supplied by people within the production, quality or environmental department. All included component manufacturing data representing the site specific data except for the label and cover. This was caused the difficulty in getting the response from the suppliers since the company was has chaotic situation caused by the global economic recession. If the data have not been available it was assumed consume almost the same amount of energy with another similar process, e.g. label for cushion and label for the airbag module.

Companies' annual and environmental reports have been used, and in many cases complemented with discussions with person in charge for the publications mainly for some unclear data. When data have not been available qualified estimations has been made based on relevant literature. The required transportations are also included in the data set.

The data for electricity represent the specific country and taken from the International Energy Agency (IEA) data on Monthly Electricity Statistics (August, 2009). On the other hand, the emissions were collected from the Hitch Hiker’s Guide to LCA book on inventory data for electricity production.

5. Methods

5.1. Data Collection

Manufacturing industry typically has numerous suppliers for one product. Certain strategy must be employed to manage the multitude of data collection activities. The following are steps applied to collect data from the contacts in the airbag manufacturing industry, in particular Autoliv's suppliers.

a. **Planning the data collection**
   The first and most important step in data collection is planning. Frequent reference to the schedule will help give a sense of how much progress has been achieved. Sometimes, the desire to further explore the life cycle and to gain more information from suppliers was strong, while some information could actually be substituted with average LCI data. In the beginning of this study, the planned time for data collection was 6 weeks, but it expanded to almost 10 weeks due to the large number of suppliers. To keep up with the schedule, calculations were started halfway through data collection. The calculation step could also be useful in formulating the most convenient way of storing the data.

b. **Collecting material summary**
   The second step of collecting data was material summary data collection, which consists of the product content with weight information. Important to mention is not to leave out any material which looks negligible in amount. That material might have significant environmental impacts. The information was obtained from the internal information system in Autoliv, i.e. the Product Lifecycle Management (PLM) that supplies information on material summary, material composition, technical drawings, research contacts, supplier contacts, etc.

c. **Recognizing the materials**
   Recognition process includes at least four kinds of information: material definition, method to produce the material, method to process the material into the product, and risk and safety information of the material. The data can be obtained primarily from PLM and the International Material Data System (IMDS). IMDS is designed and approved by automotive-related industry for the exchange the information of materials of specific product. Some additional data were available from material safety data sheets, encyclopedia, or the internet. The information was then compiled into one file. This file is important in further data collection steps, such as interviews and prioritization.

d. **Identifying first-level suppliers**
   Autoliv maintains an information system to deal with suppliers and customers, called the Autoliv Global Purchasing System (AGPS). Access into this system was requested from the Logistic department. This system provides the data of lead buyers (the Autoliv employee responsible to maintain contact with certain supplier) and Autoliv first-level suppliers (vendors supplying components directly to Autoliv). For some strategic materials, data is available for suppliers several levels up the supply chain.

e. Seeking average data

Average data means the life cycle inventory (LCI) data for raw material production, processing and end of life treatment. This information should be collected together with the file from material recognition step. LCI data represent average numbers of resource and energy use, emissions and waste generated during material life cycle. There are numbers of available free of charge LCI data such as CPM, ELCD, US LCI database with all limitations on it. More detailed and complete data are usually bundled with LCA softwares such as GaBi or Simapro.

f. Prioritization

When dealing with manufacturing industry which has numerous suppliers, it is needed to do prioritization. Prioritization pinpoints the materials to be given more effort in site-specific data collection. Prioritization was made by means of the Multi Criteria Analysis (MCA) which used five weighting factors, i.e. Autoliv-specific component, quantity, toxicity, scarcity, transportation distance, and LCI data availability. So, it is important to do all previous phases of data collection carefully.

g. Constructing the questionnaire

The design of the questionnaire needs to take into account the perception of the suppliers. Suppliers would be reluctant to fill in a long questionnaire with many pages, branch choices, and multiple blank spaces for extra comments. The survey would seems to be an unnecessary additional workload. Therefore the questionnaire needs to be concise and simple dense with substantial information but should be kept simple, which maximum 2 pages. Some LCA and environmental terms are unfamiliar to industry people working in production engineering or logistics. Those terms should be avoided and replaced with technical or financial terms. Attention should be paid to units, as different countries use different units. Questionnaire can be regarded as the most important means of data collection, so it is also necessary to consult the questionnaire to the concerned party, i.e. supervisor, intended audience, etc.

Some substantial data that should be mentioned in the questionnaire are contact information, energy and water use, specific part number, unit price, annual sales, description of production processes, material consumption and material's suppliers identity. This listed information was basic minimum information needed for calculation, allocation, result interpretation and report writing. Other information might need longer description and were best discussed over the phone, such as different energy sources, waste management practice and recycling practice. The blank questionnaire is available on Appendix.

h. Contacting lead buyer

Lead buyer is an employee responsible to manage all purchasing-related activities with one or several suppliers. Lead buyers have the most up-to-date information on suppliers and maintains personal contact with them. Some suppliers were more comfortable in cooperating in this study when the lead buyers were involved. Keeping in good contact with lead buyers will help to gain more data from suppliers in following steps.

i. **Contacting the first-level suppliers**
The questionnaire was attached in an email and in mail body text the detailed information of the on-going LCA study was described. To support credibility, it is advisable to attach the project plan also, and to mention how the supplier's contact is obtained. To establish personal rapport, emails were followed up by phone calls the day after, referring to the email. Some LCA practitioners might be more comfortable starting with phone calls. In this study emails are the preferred way of self introduction. The supportive suppliers would answer the questionnaire and the survey could then proceed to the second-level suppliers. Some supplier contacts needed verification on filling in the questionnaires, or referred to other employees or even other branch offices.

j. **Contacting the second-level suppliers and further**
The same technique was used to contact the second-level suppliers and further to the cradle of the materials. Suppliers sometimes disregard email and questionnaire, so it is important to remind them by calling over the phone, and giving a certain deadline to answer the questionnaire. Furthermore, almost 90% of the suppliers contacted with email need to be reminded by calling. The issue to disregard the email is increasing since the second suppliers not directly connected with the institution of practitioner. Again it is a good practice to refer to the previous suppliers and explain the benefits of participating in the study.

k. **Dealing with a lack of response and confidentiality issue**
It is not surprising when some suppliers do not give any quick response. They had different reasons for not replying soon. Those included insufficient time, the need to ask for permission from a higher level manager, the need to verify the purpose of the study, computer problem, etc. Some negative response were statement that the information was confidential, that they did not do business with Autoliv, or that Autoliv only constituted a small portion of their business. Sometimes suppliers needed formal agreement in matter of confidentiality. As a representative of Autoliv, it was important to always employ positive business-like tone and good manners when dealing with the suppliers even if they showed no intention to cooperate in the study.

l. **Compiling information and visual media**
The collected and contacted suppliers expanded to eighty-four and continued to expand. The increasing numbers of suppliers made it difficult to update the information to the intended audience. So, it was necessary to accompany the data collection processes with visual media, i.e. world map, printed graph of the flowchart, LCI data-hyperlinked excel spread sheet, color marking paper, etc. The visualization also helped keeping track of the progress of the study.

m. **Complementing the information**
While data collection processes continued, the calculation process was started and by the evolving time the lacking of data was discovered. So, good supplier's databases and communication with suppliers have to be kept.

Of the total 81 suppliers, 60 suppliers (74%) were cooperative and willing to participate in the study. However, the quality of supplied data varies greatly due to allocation problems and confidentiality issue in some required information. Suppliers with strict confidentiality issues constitute 16% (13 suppliers). Due to out-of-date information in the system, there are 8 suppliers (10%) that have ceased doing business with Autoliv. Detailed information of suppliers is available in the Appendix.

6. Inventory Analysis

This section includes the data collection and the defining of the flowchart for the production. The processes constituting the life cycle are described as well as the means of transportation.

6.1. Flowchart

The flowchart will guide a description of the systems. In Figure 8 below the flowchart for the production of driver airbag module is shown. The airbag module consists of label, nut, cushion, can, cover and inflator. The airbag module is installed in Volvo Car and along with the car during car operation. Finally the airbags are shredded together with the car as the end of life.

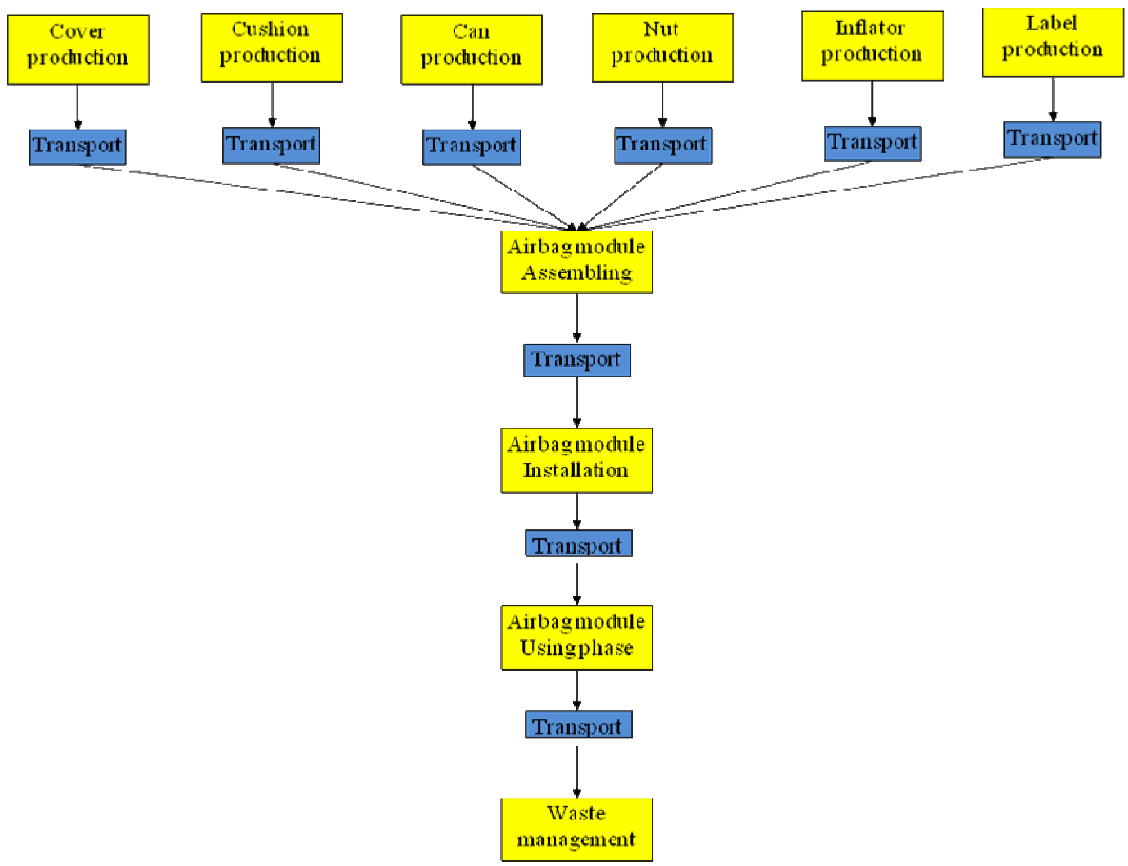


Figure 8. Simplified Flowchart for The Life Cycle of Autoliv Driver Airbag Module

6.2. Production of Label

Production of label takes place in a label manufacturer in Sweden. Materials for label are mainly low density polyethylene and adhesive. The label transported to Autoliv by truck. Flowchart for production of label can be seen at Figure 9 below.

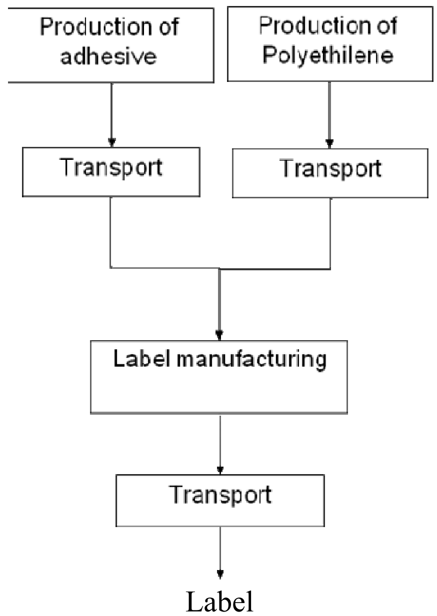


Figure 9. Flowchart of Label Manufacturing Process

Manufacturing of label is started with making polyethylene film by extruding polyethylene granule with extrusion molding machine, and then PE film edge is cut. An adhesive is added to one surface of PE film which is in this label acrylic resin was used as adhesive. The last step of label manufacturing is printing the information of label according to customer's demand. In this label, ink lacquer is used to print the label. In this study, ink has not been included since difficulty to find the life cycle inventory data. Because of the similarity in process steps for other label the processes will only be described once.

Data for the production of adhesive and polyethylene are based on generic data. Other data are site-specific, with assumptions of local producers of adhesive and polyethylene.

The complete data set for the production of label can be found in Appendix, sections **A.5.1**.

6.3. Production of Nut

The supplier of the nut is located in Sweden, but the production of nut itself takes place in Taiwan. The raw material for nut is steel bar and the nuts are then transported to Autoliv by ship and truck. The flowchart for production of nut can be seen in Figure 10.

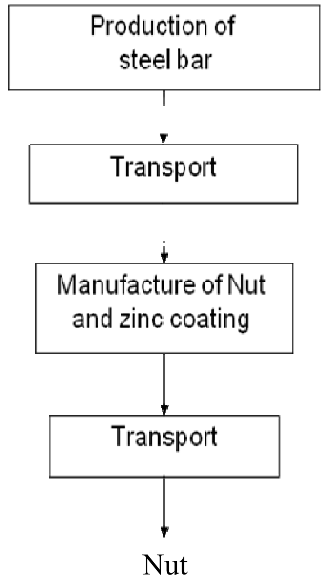


Figure 10. Flowchart of Nut Manufacturing Process

Nut productions start with incoming raw material which is steel bar. The incoming steel bar is cut to the size of the nut. The next process is tapping where the cut bar is inputted to the tapping machine to thread the parts. The next process is coating, where the threaded parts is electro-galvanized with zinc coating to give resistance of corrosion for the produced nut.

Data for the production of steel bars are based on generic data. Other data are site-specific, with assumptions of local producer of steel bars in Taiwan.

The complete data set for the production of the inner ring can be found in Appendix, section **A.5.2**.

6.4. Production of Cushion

Production of cushion takes place in Portugal. Raw materials for cushion's components are polyamide 6.6 for the fabric and thread, polyamide 6.6 reinforced with glass fiber for the stronger thread and low density polyethylene for the label. The cushion was then transported to Autoliv by ship and truck. The flowchart for production of cushion can be seen in Figure 11.

6.4.1. Production of Thread

Production of polyamide 6.6 thread takes place in Turkey. Raw material for thread production is high tenacity polyamide 6.6 yarn. The polyamide 6.6 yarn was produced in Germany. The incoming raw material then twisted in twisting machine. The thread is then dyed and finishing treatment. The thread then packed and transported to Portugal where the thread is used to seam the cushion.

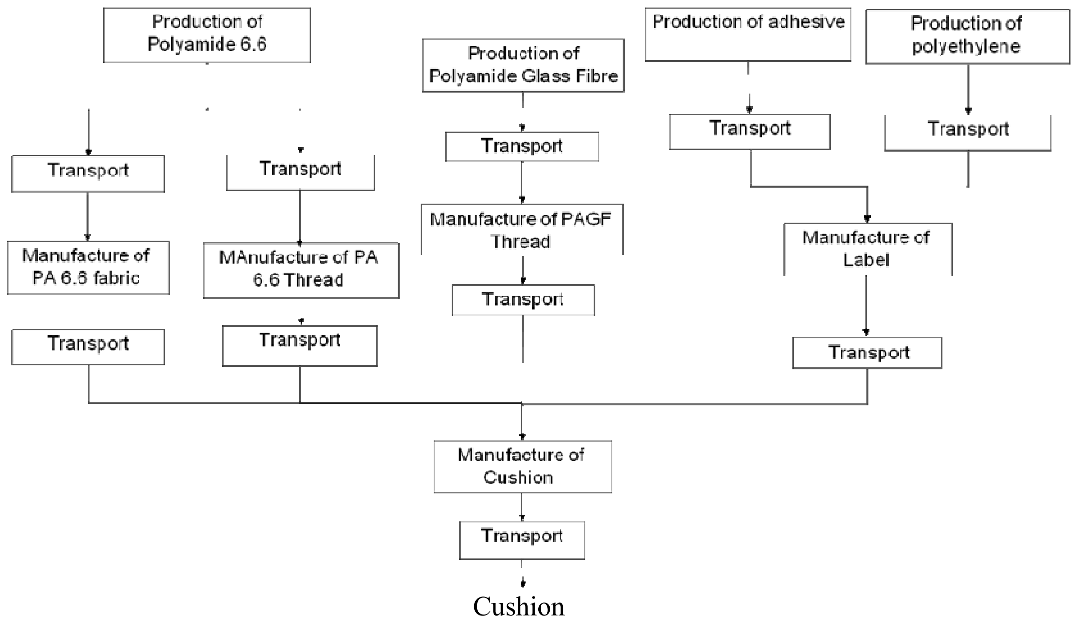


Figure 11. Flowchart of Cushion Manufacturing Process

6.4.2. Manufacturing of Fabric

Raw material for the fabric is polyamide 6.6 (PA 6.6). PA 6.6 pellets are manufactured to fabric in UK. These pellets are heated and pressurized in an autoclave into a syrupy solution. Next, the solution is extruded through a spinneret-a device that looks and works like a shower head, with long strings of PA6.6 solution coming out of the holes in the device. As the fibers emerge from the spinneret, they are cooled by air and then stretched over rollers to stabilize the molecular chains and strengthen the fibers. The yarn is then wound on spools. Yarn is fed into a circular knitting machine, which converts it into a series of loops of fabrics.

6.4.3. Manufacturing of Cushion

The incoming fabrics are spread and then cut. The next step is marking the fabric with the folding and cutting pattern. The fabric is then stamped and then up-hang the cut pieces. Each of pieces is sewed together to make insider inflator seam and the face side seam. Laser cutting is used to remove the inappropriate shape after sewing process. The two seams are closed together and then enveloped. The final airbag cushion product is then folded and labeled. The final two steps are metal detection and packing.

Data for the production of polyamide 6.6, polyamide glass fibre, adhesive, and polyethylene are based on generic data. Other data are site-specific, with assumptions of local producers of the materials.

The complete data set for production of the cushion can be found in Appendix, section **A.5.3**

6.5. Production of Can

The can is produced by a vendor in Sweden. Steel sheet is the material for can base while for the snap in-pinne use steel bar. The steel sheet is produced in the Netherlands while the steel bar is produced in UK.

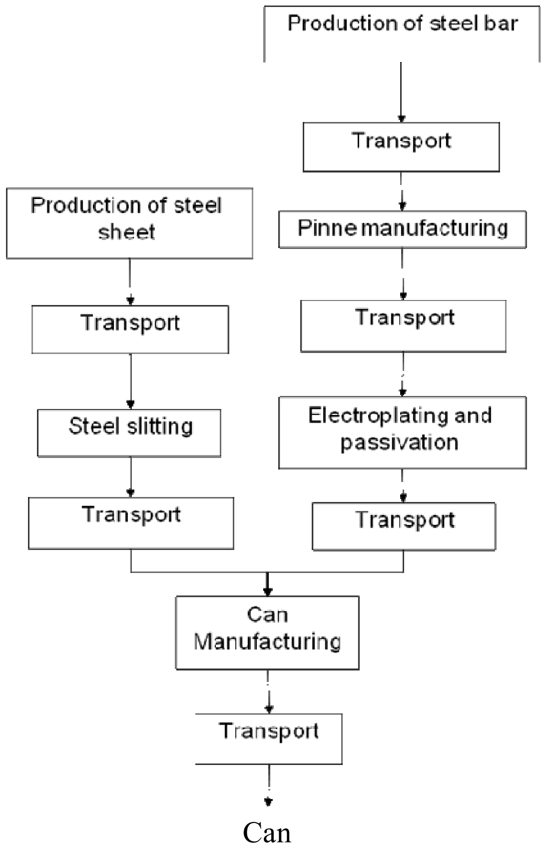


Figure 12. Flowchart of Can Manufacturing Process

The steel sheet is transported to a vendor's facility in Sweden where the sheet is slit to the desired sized. The cut steel sheet is punched using a stamping press machine to the desired form and then zinc galvanized to make the steel sheet can resist for rust and corrosion. The snap in pinne was manufactured by cold drawing of cut steel bar, also in Sweden. The snap-in pinne is then transported and assembled with the base can. The can assembly is transported to Autoliv in Vårgårda by truck.

Data for the production of steel bars and steel sheets are based on generic data. Other data are site-specific, with assumptions of local producers of both materials.

The flowchart is shown in Figure 12. The complete data set for the production of the can be found in Appendix, sections **A.5.4.**

6.6. Production of Cover

The cover is produced by a German vendor. There are two main polymer materials for the Cover. The insider-hard part of cover is made from TPS-SEBS, while the outsider-leathery part made from Ethylene Propylene Diene Monomer (EPDM). There are also Acrylonitrile Butyl Styrene (ABS), Polymethyl Metacrilate (PMMA) and aluminium as material for the emblem.

Figure 13 shows the flowchart of manufacturing process. Data for TPS-SEBS were not found and replaced with a substitute, ABS, which has similar properties. Data for wrought aluminium, ABS, PMMA, and EPDM are based on generic data. Other data are site-specific, with assumptions of local producers of the materials. The complete data set for cover production can be found in Appendix, section **A.5.5.**

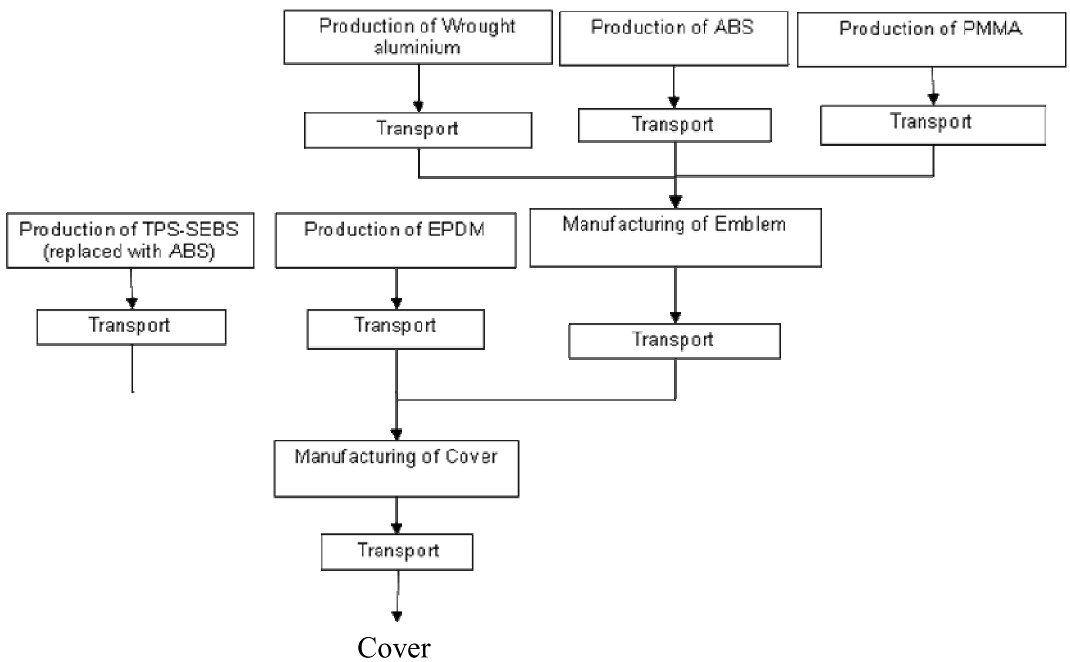


Figure 13. Flowchart of Cover Manufacturing Process

6.6.1. Manufacturing of Emblem

The emblem is manufactured in Germany. The main material for the emblem is ABS. Together with PMMA (both are also produced in Germany), ABS was formed to form emblem by injection molding. Aluminum then glued as glossy surface for the emblem. Aluminum was previously stamped to the emblem form and by using lacquer to give the logo shape for the emblem. Due to the difficulty and small quantity of the lacquer, this material is not included in this study. The manufactured emblem then transported to cover manufacturer by truck.

6.6.2. Manufacturing of Cover

The cover consists of two layers. The resinous plastic for the inside layer and flanges of cover is made from ABS which is molded with a special design of molding template. This molding template will provide this insider part of cover to have a flange that allow this airbag cover to be mounted for securing it to the mounting plate of airbag module can. In another hand the molding provides the airbag cover a thin shaped separation line that will break and allow the flaps or door portion formed by the pattern to bend back allowing deployment of the airbag.

The ABS in granule form is molded using injection molding which is injected behind a layer of natural leather made of EPDM that roughened inner surface with strands which will embed within the moldable material during formation. A special adhesive is also introduced prior to injection molding that will allow enhanced mechanical bond between the two surfaces. In this study, the adhesive is excluded.

After injection of the resinous material, the airbag cover is allowed to cure and/or set up with the mold apparatus in closed position, typically for a period of 30 to 120 seconds. Thereafter, the still warm, flexible, partially cured airbag cover may be pulled away from the mold surface and lifted off that surface. The part is then allowed to fully cure prior to attach with emblem, finishing, packaging and delivery. The airbag cover is then transported from Germany to Autoliv in Vårgårda, Sweden.

6.7. Production of Inflator

Manufacturing of inflator consist of many different small components. There are TBD diffuser, initiator, base, adapter, seal washer, igniter tube, cup, cap, TBD filter, gas generant, pad damper, retainer disk, shunt ring, caution label, tracing label and clinching stud. Fig. 14 below presents a simplified diagram of the components of an inflator.

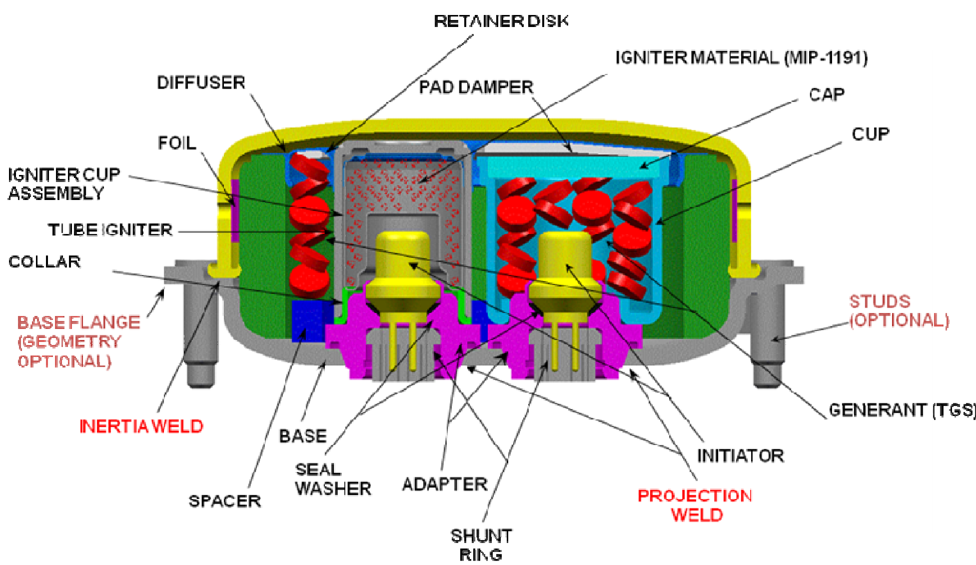


Figure 14. Drawing of Inflator's Components
Source: Autoliv internal document (2009)

6.7.1. Manufacturing of TBD Diffuser

Diffuser mainly consists of steel and attached with aluminum foil by means of acrylic. The Diffuser is manufactured in Italy where the steel sheet is cut and stamped. The aluminum foil is manufactured in Germany and together with acrylic resin to form aluminum foil that will be attached to the steel diffuser.

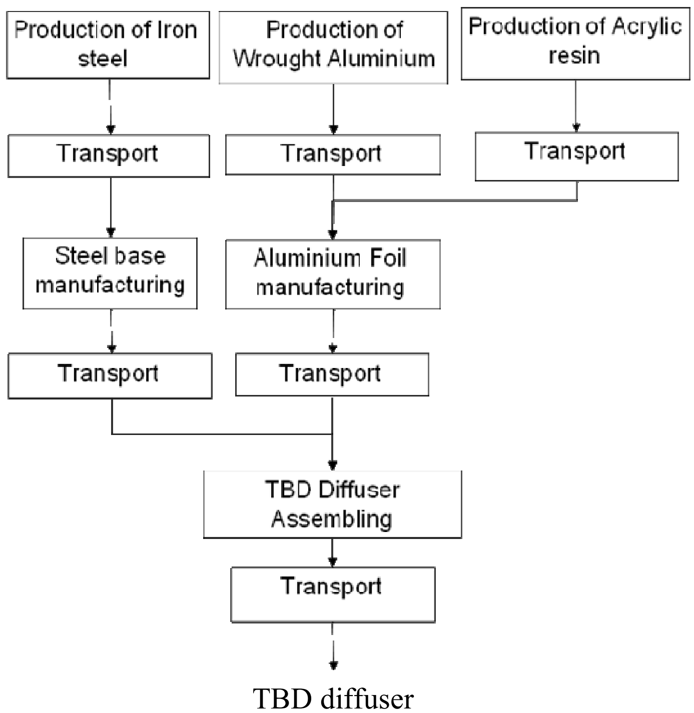


Figure 15. Flowchart of TBD Diffuser Manufacturing Process

Aluminum foil is made from aluminum slab (rolling ingot), which is first rolled into foil stock, i.e. the specific input for foil fabrication. In this LCA study, the starting material is referred to as "aluminum ingot'' when it comes from an external primary or secondary aluminum plant. It is also produced by re-melting process scrap internally within this system (Ingot re-melting and casting) and this input is referred to as "casting scrap". The process steps for aluminum foil production are sawing and scalping, preheating, hot rolling, cold rolling foil stock, cold rolling single, final anneal, finishing and packaging. The aluminum foil then transported to Italy where TBD diffuser are assembled and finally delivered to Autoliv Romania by truck. The complete process is shown in Figure 15.

6.7.2. Manufacturing of Initiator

Initiator is part of inflator that will generate charge to make the gas generant to deploy. Initiator assembly consists of initiator cup, initiator cap, bridge-wire, pin, insulation, charge holder and sealing. Initiator is manufactured by an Autoliv subsidiary in US. The inflator components are supplied and manufactured mainly in US.

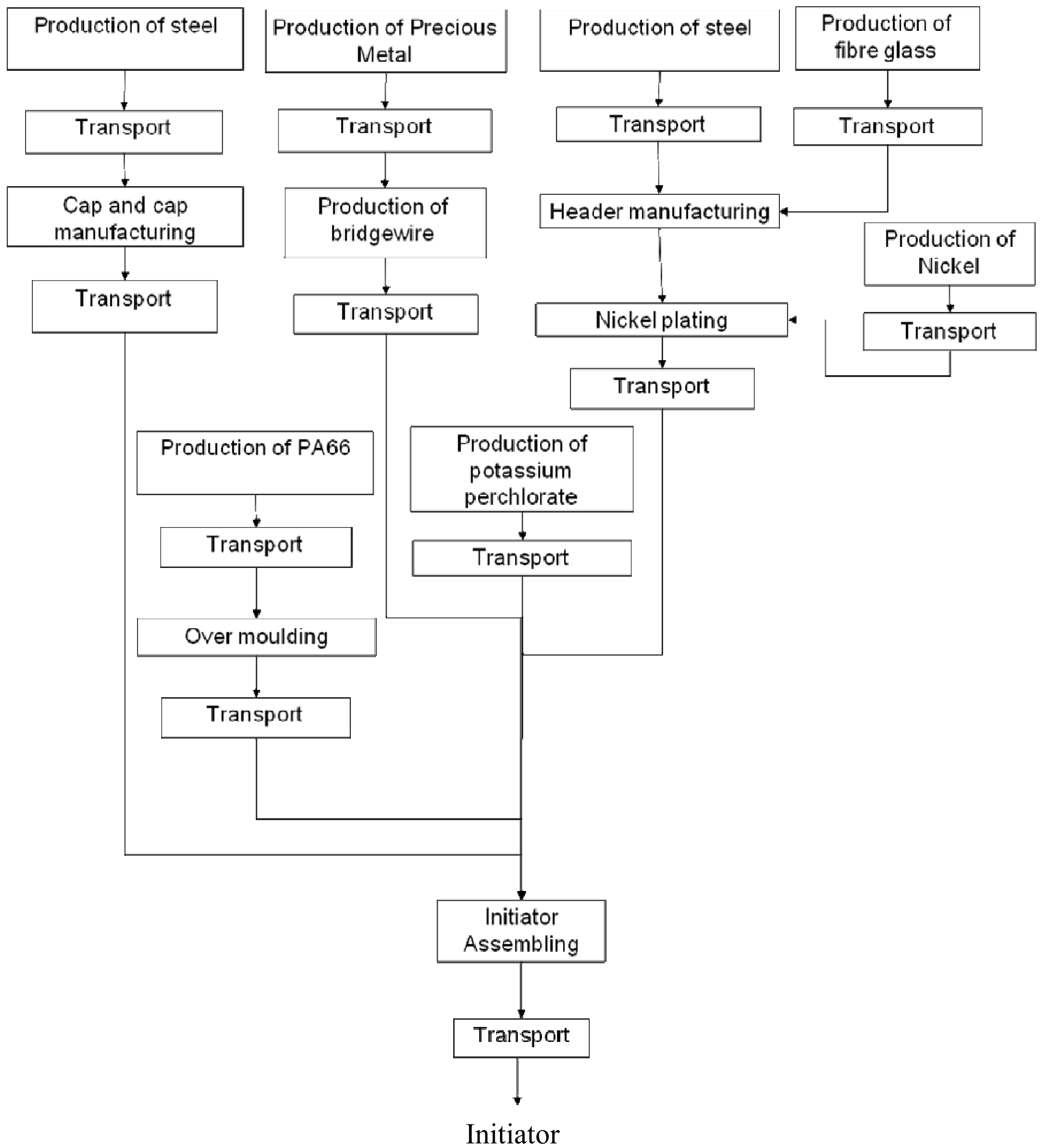


Figure 16. Flowchart of Initiator Manufacturing Process

Figure 16 shows the processes involved in the manufacturing of initiator. The initiator cup and cap are two components that give case to the initiator. Both are made from stainless steel and manufactured in US. The steel are slit to desired size and then manufactured to form a cup and cap by stamping.

Another component, the bridgewire, is mainly made of precious metals like palladium which is drawn into form. However, in this study, this material was excluded due to difficulty of getting the data. During deployment, the bridgewire will burn to generate heat that make the gas generant deploys. First step in bridgewire manufacturing is the assembly of all components into fixtures. The assembly is fused in furnace. After fusing, the part is disassembled from fixture, etched, gold plated, ground, inspected, and packed for shipment to customer. The sealing is made from polyamide 6.6 where it is injection molded.

The cover for the insulation is made from extrusion of ETFE in which in this study is replaced by PET since the difficulty to find the LCI data for ETFE. The PET sheet is thermoformed into insulator cap on a web. The parts are punched out of the web and placed in a sealed Anti-Static bag.

The header is made from steel which is coated with nickel and gold which is ceramic glass in the inside. The header is manufactured by an American vendor and transported to Autoliv facility by truck. The chargeholder is manufactured from stamped steel.

Finally, the initiator is assembled from each of the components. Propellant material (potassium perchlorate and zirconium) are mixed from suppliers and then dried. Bridgewire is welded to incoming header. Chargeholder is welded to bridgewire assembly to make chargeholder subassembly. Propellant loaded into chargeholder subassembly. Cruciformed cup placed over chargeholder and welded in place. Insulation cover installed on cruciformed cup. Electric check and x-ray inspection performed. Pre-molded subassembly sent to molding operation for overmolding. Finished part packed for shipment to Autoliv Romania by large ship and truck.

6.7.3. Manufacturing of Base

The base for the inflator is made from steel, which is manufactured by slit the steel sheet into the desired size and then punched into form by stamping. The base for the inflator is manufactured in Italy and transported to Autoliv Romania by truck. The flowchart is shown in Figure 17 below.

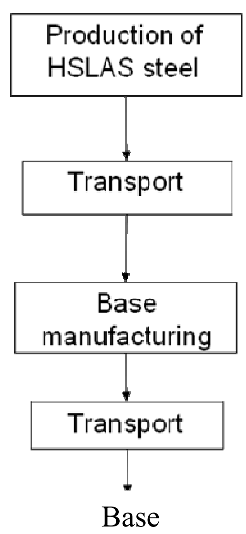


Figure 17. Flowchart of Base Manufacturing Process

6.7.3. Manufacturing of Adapter

Adapter for the inflator is made from steel, which is manufactured by slit the steel sheet into the desired size and then punched into form by stamping. The adapter is manufactured in France and transported to Autoliv Romania by truck. The flowchart is shown in Figure 18 below.

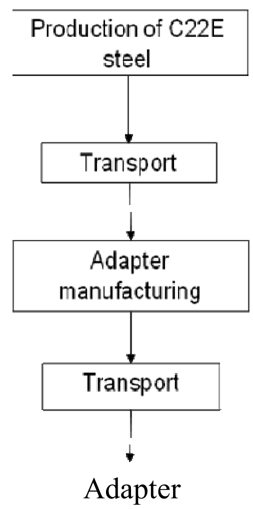


Figure 18. Flowchart of Adapter Manufacturing Process

6.7.5. Manufacturing of Seal Washer

Seal washer that help to hold the initiator on it place on top of adapter is made from Acrylonitrile Butyl Rubber (NBR). In this study, NBR was replaced with EPDM since the almost similarity of both material's properties. The seal washer is manufactured in France by injection molding. The seal washer product is then transported to Autoliv Romania by truck. The flowchart is shown in Figure 19.

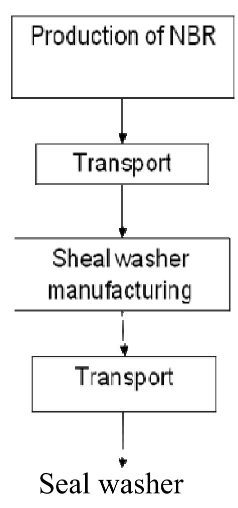


Figure 19. Flowchart of Seal Washer Manufacturing Process

6.7.6. Manufacturing of Igniter Tube

The igniter tube is consisting of the tube made from stamped carbon steel. Inside it, there is propellant which is mixed of guanidine nitrate, potassium nitrate, boron and ethanol. The igniter tube is manufactured in US and then transported to Autoliv Romania by large ship and truck. The flowchart is shown in Figure 20 below.

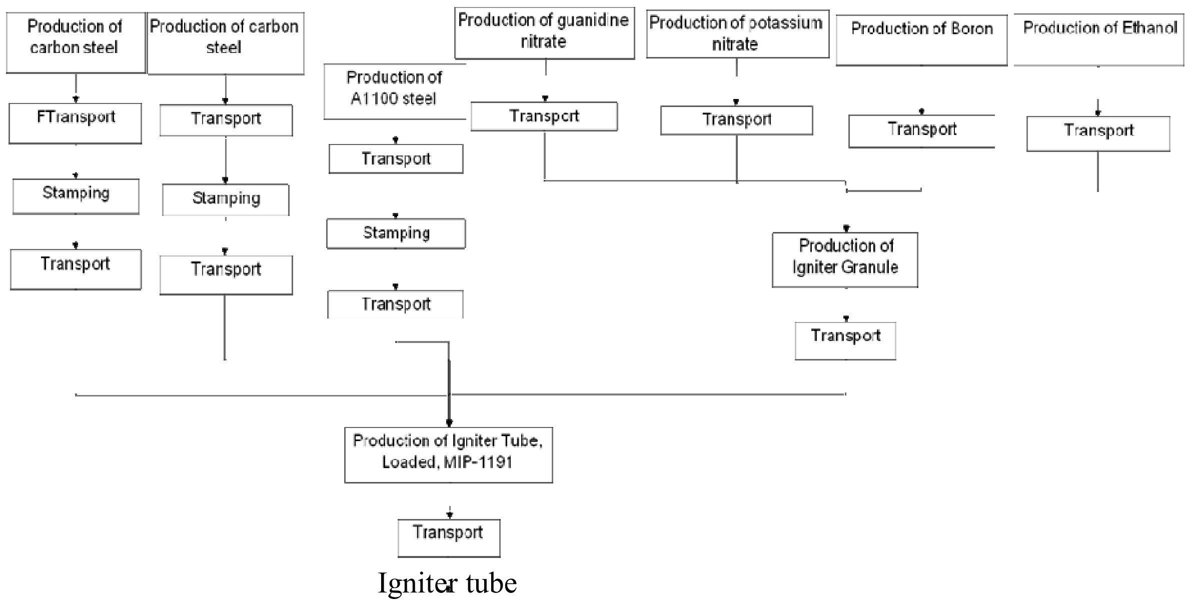


Figure 20. Flowchart of Igniter Tube Manufacturing Process

6.7.7. Manufacturing of Cup and Cap

The cup and cap for the inflator are made of steel alloy. Steel sheets are slit into the desired size and then punched into form by stamping. The flowchart is shown in Figure 21 below.

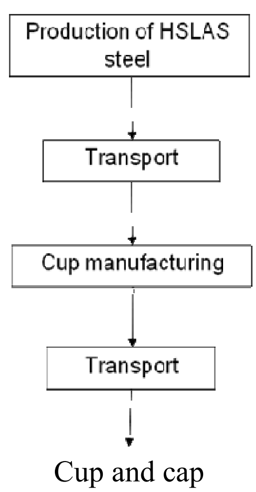


Figure 21. Flowchart of Cup and Cap Manufacturing Process

6.7.8. Manufacturing of TBD Filter

TBD filter has a function in inflator to screen the unwanted slag that produced during gas generant deployment. Furthermore, it helps to reduce the temperature of the effluent gases. TBD filter screen manufactured from carbon steel and stainless steel. In addition, ceramic paper was used to increase the cooling capability of TBD filter. TBD filter is manufactured in US and transported to Autoliv Romania by large ship and truck. The flowchart is shown in Figure 22 below.

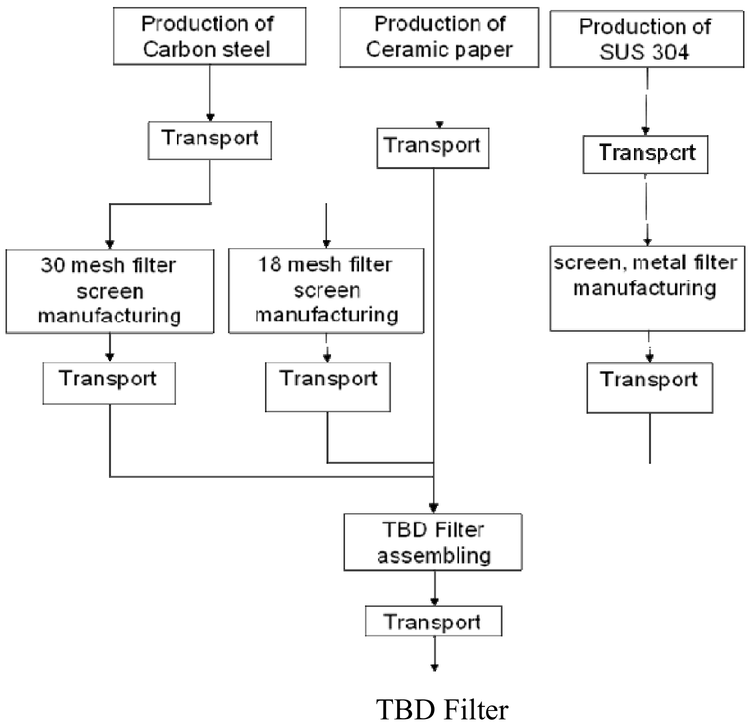


Figure 22. Flowchart of TBD Filter Manufacturing Process

6.7.9. Manufacturing of Gas Generant

Gas generant in this study is represented by guanidine nitrate which is made from urea and ammonium nitrate. Other chemicals like aluminum oxide, BCN and silica powder are added to reduce and prevent the toxic release of gases that emitted during deployment. The guanidine nitrate and other chemicals are manufactured in Canada and transported to Promontory, Utah, US where the gas generant is mixed together. The mixed gas generant then transported to Autoliv Romania by using large ship and truck. The flowchart is shown in Figure 23 below.

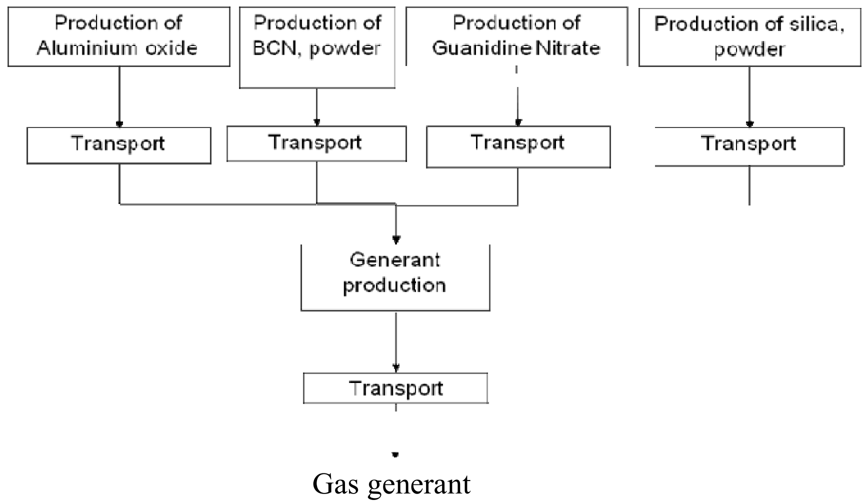


Figure 23. Flowchart of Gas Generant Manufacturing Process

6.7.10. Manufacturing of Pad Damper

The pad dampers that help to hold up the cup and cap are made from glass fiber. The pad damper is manufactured by a vendor in Romania. The pas damper is manufactured in to the desired shape by injection molding. The pad damper product is then transported to Autoliv Romania by truck. The flowchart is shown in Figure 24 below.

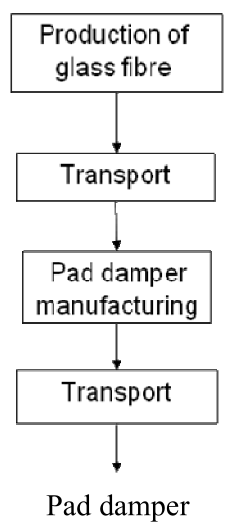


Figure 24. Flowchart of Pad Damper Manufacturing Process

6.7.11. Manufacturing of Retainer Disk

The pad damper is manufactured in Germany. The pas damper is made from carbon steel (DC04) which is manufactured in to the disk form by stamping. The retainer disk product is then transported to Autoliv Romania by truck. The flowchart is shown in Figure 25 below.

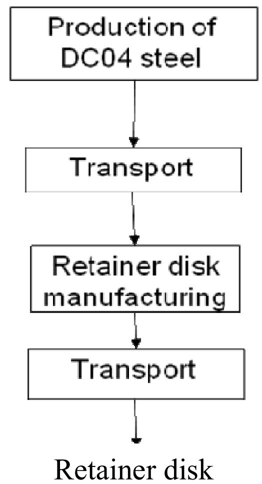


Figure 25. Flowchart of Retainer Disk Manufacturing Process

6.7.12. Manufacturing of Tracing Label

The production of label can be seen at production of label previously. The difference is the material for this tracing label is paper instead of polyethylene. The label is manufactured in Germany and transported to Autoliv Romania by truck. The flowchart is shown in Figure 26 below.

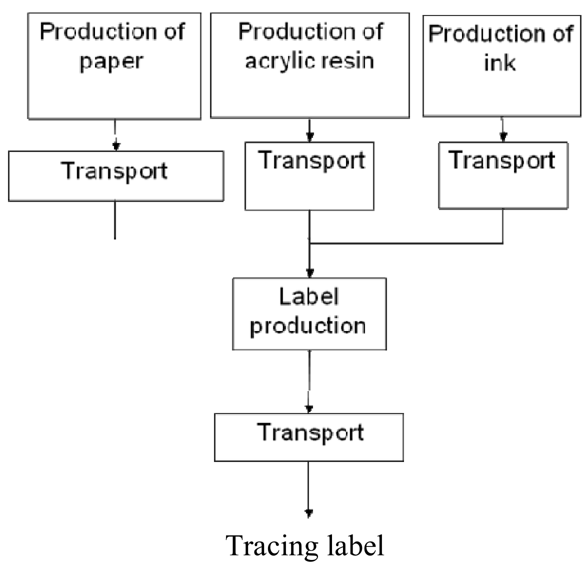
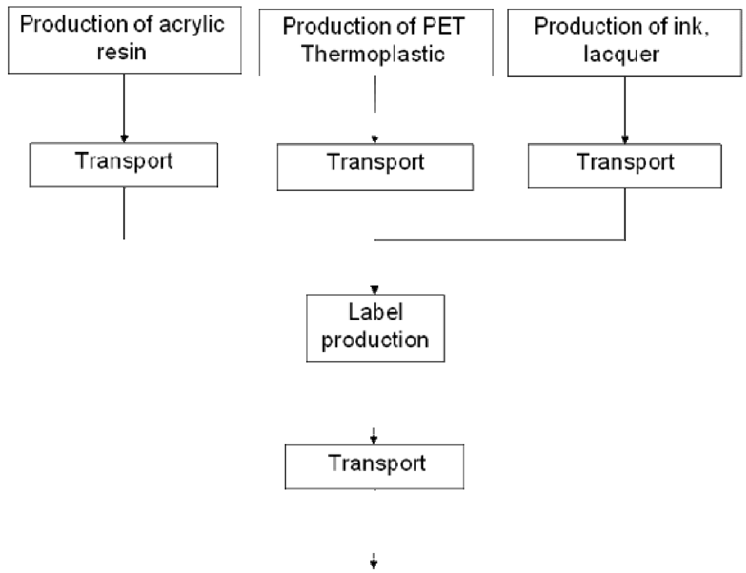


Figure 26. Flowchart of Tracing Label Manufacturing Process

6.7.13. Manufacturing of Caution Label

See the production of label above. The difference is the material for this caution label is PET instead of polyethylene, to withstand the heat generated during airbag deployment. The caution label is manufactured in Germany and transported to Autoliv Romania by truck. The flowchart is shown in Figure 27.

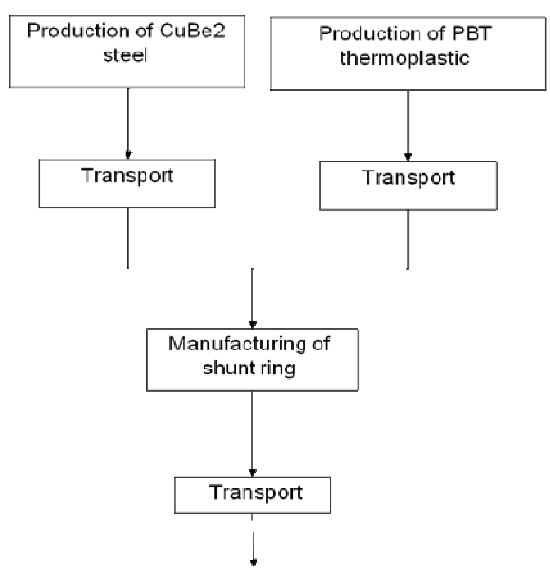


Caution label

Figure 27. Flowchart of Caution Label Manufacturing Process

6.7.14. Manufacturing of Shunt Rings

Shunt ring that help to hold up initiator are made from PBT and carbon steel. The shunt ring is manufactured in Germany. The shunt ring is manufactured in to the desired shape by injection molding. The pin made from carbon steel that is coated with gold and nickel is then attached to the shunt ring to become the final product and then transported to Autoliv Romania by truck. The flowchart is shown in Figure 28.



Shunt ring

Figure 28. Flowchart of Shunt Ring Manufacturing Process

6.7.15. Manufacturing of Self Clinching Stud

The stud manufacturing includes several steps of treating the carbon steel (production of steel rod, cold head, roll threading, heat treatment, and plating) before visual inspection of the final product. The clinching stud is manufactured in France and the final product is transported to Autoliv Romania by truck. The flowchart is shown in Figure 29 below.

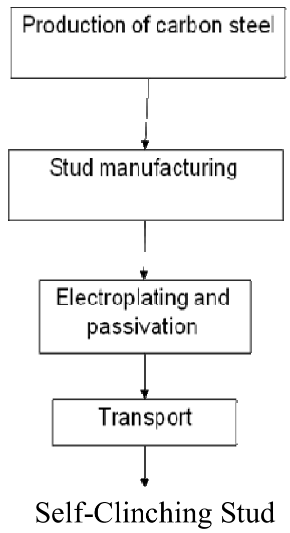


Figure 29. Flowchart of Stud Manufacturing Process

6.7.16. Inflator Assembly

The assembly of inflator consists basically of the welding of metal parts, pouring in a certain amount of gas generant, leakage check by using helium, electrical check, and putting on labels. The final inflator product is sent from Autoliv Romania to Autoliv Sverige in Vårgårda by truck.

For all processes in the inflator cradle-to-gate life cycle, data for most raw materials such as metal alloys and polymers are based on generic data. Quantitative data for the chemical mixtures of gas generants are unfortunately confidential, eventhough general knowledge about the components and processes are available from internal and external sources. However, in a weight basis gas generants constitute a small part of the final product of driver airbag, thus the lack of data does not imply large uncertainty in the final aggregated numbers. Data for other processes, including transports, are derived from suppliers' information.

6.8. Airbag Assembly

The airbag cushion are received and inspected for defects, by being inflated and checked for any seam imperfections. The cushion is then mounted to the tested inflator assembly. Next, the airbag cushion is folded, and the cover is installed. Finally, the completed module assembly is labelled and inspected. The airbag module assemblies are packaged in boxes for shipment and then sent by truck to the customer, Volvo Cars Ghent, Belgium, to be installed in cars.

6.9. Airbag Installation

The remaining components of the air bag system—the crash sensors, the electrical control unit, the steering wheel connecting coil, and the indicator lamp—are combined with the air bag module during car assembly at Volvo Cars Ghent plant in Belgium. All those components are connected and communicate through a wiring harness. Energy consumption, water consumption, and wastes generation related to this process are assumed to be negligible.

6.10. Use Phase

To model the use phase of the airbag, a study by Subic (2006) was used to allocate the environmental impact associated to airbag during car's lifetime. The associated impacts mainly come from increased fuel consumption due to the increased total weight by the addition of the airbag module. The method used to allocate the fuel consumption to the individual vehicle components is the Incremental method (Subic, 2006). It is assumed that the proportion of the fuel consumption of a component compared to the fuel consumption of the car can be obtained from the ratio between the component weight and the car weight multiplied by a factor *c*. The factor *c* represents the Fuel Consumption Reduction Value (FRV) which is used to incrementally offset mass proportional allocation of fuel consumption caused by the airbags.

$$Ccomp./Ccar = c * Mcomp./ Mcar \quad (1)$$

Where:

Ccomp = fuel consumption of the component
Ccar = fuel consumption of the car
c = fuel consumption reduction value
Mcomp = component weight
Mcar = car weight

Using basic FRV data from EUCAR (European Council for Automotive R&D) members, a value of 0.30 is chosen. Ccar is known for every kind of car. Referring to the New European Driving Cycle (NEDC), for a small car, e.g. Volvo C30, the fuel consumption is 8.4 liters/100km. The weight of the car and the airbag are also known (1200 kg and 1.5680 kg, respectively). Hence, it is possible to calculate the fuel consumption associated to the airbag. Based on EUCAR-automotive LCA guidelines, the lifetime is chosen to be 150,000 km for small and medium cars (less than 1500 kg).

As for comparison between the environmental impacts of airbag to a whole car, the study conducted by Schweimer (2000) provides detailed information (Fig. 30) of the use phase for a VW Golf car. The operation situation of the car is that the lifetime is 10 years, with 150,000 km of driven distance, maintenance checks every 15,000 km (10 times during the entire lifetime), and 180 times of washing. It is also assumed that not much part is replaced during maintenance. That is the reason that the replacing parts are not included in this study. To make calculation easier, it was also assumed that the airbags were not deployed during the lifetime of the car, i.e., the car has not got into any accident that triggered the airbag to deploy. Figure 30 below shows the diagram of the use phase of a car, which can be used to calculate the use phase of an airbag.

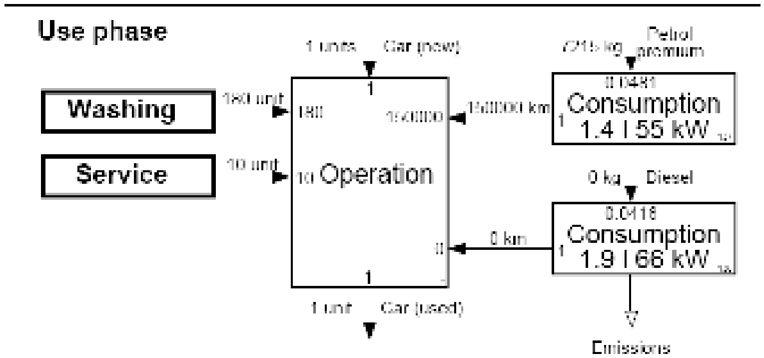


Figure 30. The Use Phase of A Car (Schweimer, 2000)

6.11. End of Life

The average life time for a car in European and American region can be assumed to be 10 years (Schweimer, 2000). The studied product of airbag was installed in the Volvo C30 series, first launched in late 2006. This means that currently virtually all of these cars have not yet reached the end of their life yet. At this stage it is not absolutely clear how the Volvo C30 will be recycled or disposed of at least 5 years from now. Today recycling rate for car is about 80% in developed countries, and the same rate is assumed for airbags. This assumption is based on the statement from Volvo environmental department personnel (Volvo, 2009). The remaining 20% in weight consist mainly of heterogeneous mix of materials such as resins, rubber, glass, textile, etc. (Toyota, 2002)

There are different end of life scenario for airbags. In Japan and Europe, the un-deployed airbag is removed from the End of Life Vehicle (ELV) and collected prior to ELV shredding (Toyota, 2002). The airbag polyamide cushion is recycled and used for making vacuum surge tanks since 1998 (Ikebuchi, 1998). In US, the module airbag is shredded together with the ELV after the airbags are deployed (USCAR, 2002). Prior deployment inside the ELV before shredding is also recommended by Volvo.

In this study, the studied airbag is assumed to be deployed inside the ELV before shredding, following the standard practice in the United States and Volvo's recommendation. This choice is partly based on the sales share of Volvo C30 car with US as the second largest market (11%) of total C30 sales in 2008 (Volvo Car Corporation, 2009). See Table 2 below.

Table 2. Market Share of Volvo C30 in 2008

United Kingdom	5,054	12.65
USA	4,299	10.76
Germany	3,236	8.10
Sweden	2,720	6.81
France	2,717	6.80
Others	21,937	54.89
Total	39,966	100.00

By this assumption, after deployed the next end-of-life scenario for airbags follows the end of life of a car. The model used to describe end-of-life practices for ELV is according to the study of Schweimer (2000) and essentially represents European region model of end of life of car (Figure 31). The recovery of secondary materials, e.g. aluminum alloys, requires processing steps which have not been comprehensively researched for this inventory. The discussed results in this study only cover the incineration and the disposal, i.e., landfilling. As for comparison for end of life for a car, a study conducted by Sullivan (1998) provides information of end of life for a sedan class car in US region.

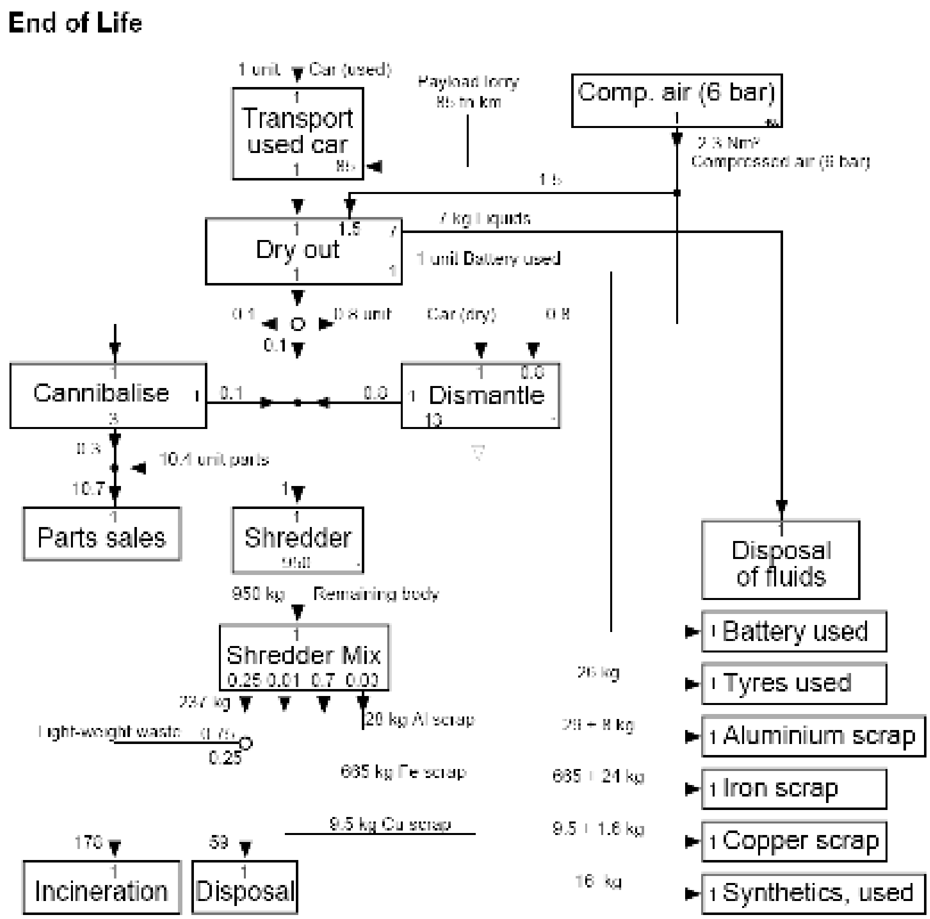


Figure 31. The End of Life of A Car (Schweimer, 2000)

The second scenario for end of life of an airbag, i.e., dismantling the airbags, was conducted as to give rough estimations on improvement idea for an alternative end of life scenario in the future. The calculation mainly covers the emissions of gases from airbag deployment and emissions from transportation of deployed airbag module to Vårgårda, Sweden. This will be discussed in Section 10.2.

7. Inventory Results

In this section the inventory results concerning air emissions (selected substances), energy consumption and total waste for the airbag module's components production, use phase and end of life are presented.

7.1. Inventory of the Production Phase

7.1.1. Label

The activities included as technical system for producing label are:
- Production of adhesive
- Transport of adhesive
- Production of Polyethylene
- Transport of Polyethylene
- Manufacture of Label
- Production of electricity

Resource use and emissions data are available in the Appendix A.5.1. The dominant process in label manufacturing is the production of polyethylene, which consumes the largest portion of energy and resources and emits the largest amount of pollutants. Water consumption for the production and transportation of label for one airbag module amounts to 0.048 kg. The associated waste is shown in Table 3 below.

Table 3. Total waste, elementary and non-elementary for the production and transportation of label for one airbag module

Waste	Elementary	Non-elementary	Total	Unit
	0,000	0.075	0,075	gram

7.1.2. Nuts

The activities included as technical system for producing nuts are:
- Production of steel bar
- Transport of steel bar
- Manufacture of nut
- Production of electricity

Resource use and emissions data are available in the Appendix A.5.2. The dominant process in nut manufacturing is the production of steel bar, though nut manufacturing is comparably important as well. Water consumption for the production and transportation of nuts for one airbag module amounts to 26.7280 gram. The waste is shown in Table 4.

Table 4. Total waste, elementary and non-elementary for the production and transportation of nuts for one airbag module

Waste	Elementary	Non-elementary	Total	Unit
	0.370	4.325	4.695	gram

7.1.3. Cushion

The activities included as technical system for producing cushion are:
The activities included as technical system for producing cushion are:

- Production of polyamide 6.6
- Transport of polyamide 6.6
- Manufacture of polyamide thread
- Transport of polyamide 6.6 (for fabric)
- Manufacture of polyamide fabric
- Production of polyamide glass fiber (PAGF)
- Transport of PAGF
- Manufacture of PAGF thread
- Production of adhesive
- Transport of adhesive
- Production of polyethylene
- Manufacture of label
- Transport of label
- Manufacture of cushion
- Transport of cushion
- Production of electricity

Resource use and emissions data are available in the Appendix A.5.3. The dominant process in cushion manufacturing is the production of polyamide 6.6, both in terms of resource and energy use and emissions. Water consumption for the production and transportation of cushion for one airbag module amounts to 6.6859 kg. The associated waste is shown in Table 5 below.

Table 5. Total waste, elementary and non-elementary for the production and transportation of cushion for one airbag module

Waste	Elementary	Non-elementary	Total	Unit
	146.487	5.371	151.858	gram

7.1.4. Can

The activities included as technical system for producing can are:

- Production of zinc
- Transport of zinc
- Production of steel bar
- Cutting and cut drawing of steel bar
- Production of steel sheet
- Transport of steel sheet
- Manufacture of snap-in pin
- Coating of snap-in pin
- Transport of snap-in pin
- Slitting of steel sheet
- Transport of slatted steel sheet
- Manufacture of can

- Transport of can
- Production of electricity

Resource use and emissions data are available in the Appendix A.5.4. The dominant process in can manufacturing is the production of steel sheet, both in terms of resource and energy use and emissions. Water consumption for the production and transportation of can for one airbag module amounts to 4.6338 kg. The associated waste is shown in Table 6 below.

Table 6. Total waste, elementary and non-elementary for the production and transportation of can for one airbag module

Waste	Elementary	Non-elementary	Total	Unit
	8.833	368.847	377.680	gram

7.1.5. Cover

The activities included as technical system for producing cover are:
- Production of EPDM
- Transport of EPDM
- Production of ABS
- Transport of ABS
- Production of PMMA
- Transport of PMMA
- Production of aluminum
- Transport of aluminum
- Manufacture of emblem
- Manufacture of cover
- Transport of cover
- Production of electricity

Resource use and emissions data are available in the Appendix A.5.5. The dominant process in cover manufacturing is the production of plastics (EPDM, ABS, and PMMA), both in terms of resource and energy use and emissions. Water consumption for the production and transportation of cushion for one airbag module amounts to 11.1648 kg. The associated waste is shown in Table 7 below.

Table 7. Total waste, elementary and non-elementary for the production and transportation of cover for one airbag module

Waste	Elementary	Non-elementary	Total	Unit
	0.281	3343.404	3343.685	gram

7.1.6. Inflator

The activities included as technical system for producing inflator are:
- Manufacturing of inflator
- Manufacturing of metals (steel alloys, aluminium, silver, palladium, copper, zirconium, magnesium)
- Manufacturing of metal parts (diffuser, base, adapter, cruciformed cup, chargeholder, header, bridgewire, tube, cup, cap, barrel, filter screens, pad dampers, stud)
- Gold, nickel, and zinc coatings
- Manufacturing of raw materials (acrylic resin, polyamide 6.6, PET, ceramic glass, elastomer, ceramic paper and glass fiber)
- Manufacturing of foil
- Manufacturing of initiator
- Manufacturing of insulation cover
- Manufacturing of seal washer
- Manufacturing of igniter granule and its constituents
- Manufacturing of retainer disk
- Manufacturing of tracing and caution labels
- Manufacturing of shunt rings
- Manufacturing of gas generant and its constituents
- Transportations between manufacturing sites
- Electricity generation

Resource use and emissions data are available in the Appendix A.5.6. The dominant process in inflator manufacturing is steel manufacturing. Water consumption for the production and transportation of inflator for one airbag module amounts to 56.6384 kg. The associated waste is shown in Table 8 below.

Table 8. Total waste, elementary and non-elementary for the production and transportation of inflator for one airbag module

Waste	Elementary	Non-elementary	Total	Unit
	961.641	86.612	1048.253	gram

7.2. Use Phase

The included activities as technical system in use phase of a car include car operation fuel consumption, cleaning, and maintenance. However, for an airbag, the only relevant aspect is the fuel consumption. The airbag modules are calculated to consume 3072 MJ, or 96 litres of fuel during the car's lifetime in use. The emissions are shown in Table 9 below. There is no calculated water consumption in the use phase that can be directly associated to existence of ten airbag modules inside a car. Similarly, the use of airbags does not generate wastes.

Table 9. Emissions to air from the use phase associated with the existence of ten airbag modules inside a car

Substance	Unit	Total	Dominant process
CO_2	kg	224.73	Airbags related fuel consumption
CO	gram	156.34	Airbags related fuel consumption
HC	gram	0.02	Airbags related fuel consumption
NO_X	gram	29.31	Airbags related fuel consumption
SO_2	gram	29.31	Airbags related fuel consumption

7.3. End of Life

The included activities as technical system in use phase of airbag module are:
- Used car transport to shredding site
- Shredding and sorting
- Land filling
- Incineration

The data of emissions, energy consumption, and total waste are shown in Table 10, 11, and 12, respectively. The dominant process in this phase is shredding. Water consumption in the end of life phase associated to existence of ten airbag modules inside a car amounts to 0.052 kg.

Table 10. Emissions to air from end of life phase associated with the existence of ten airbag modules inside a car

Substance	Unit	Total	Dominant process
CO_2	gram	1872.100	Shredding
CO	gram	8.925	Shredding
HC	gram	2.221	Shredding
NO_X	gram	10.532	Shredding
SO_2	gram	4.116	Shredding
CH_4	gram	1.882	Shredding
Particulates	gram	3.227	Shredding

Table 11. Energy consumption from end of life phase associated with the existence of ten airbag modules inside a car

Sources	Unit	Total	Dominant process
Electricity	MJ	1.777	Shredding
Crude oil	MJ	19.346	Shredding
Hard coal	MJ	3.780	Shredding
Natural gas	MJ	1.268	Shredding

Table 12. Total waste from end of life phase associated to existence of ten airbag modules inside a car

Waste	Elementary	Non-elementary	Total	Unit
	0.000	8.127	8.127	gram

8. Impact Assessment

This chapter presents the results of classification and characterization of environmental impacts that can be associated to airbag. The calculation covers from production, use phase and end of life, including the electricity generation and transportation. To get in deep understanding to the airbag itself, the impact assessment result from production phase was further expressed and discussed.

8.1. Global Warming

Substances that contribute to global warming are emitted from all of the studied activities. Emissions of these substances from each of airbag life cycle phase have been characterized and added as CO_2 equivalents. The results are shown in the table below.

Table 13. Global warming (100 years) of airbag (CIT Ekologik, Index list May 2000)

Substance	Environment	Quantity	Factor	Result	Unit
Aldehydes	Air	0.0003	11.00	0.0033	g
BOD, fossil	Water	0.0073	1.38	0.0101	g
BOD5, fossil	Water	0.0005	1.38	0.0007	g
CH_4	Air	9.8062	21.00	205.9299	g
CO_2	Air	8014.3708	1.00	8014.3708	g
CO	Air	10.2633	3.00	30.7900	g
COD, fossil	Water	7.9463	1.38	10.9659	g
Hydrocarbon	Air	1.7991	11.00	19.7896	g
N_2O	Air	1.9999	310.00	619.9624	g
NOx	Air	19.6742	7.00	137.7197	g
PAH	Air	0.0005	11.00	0.0057	g
Propene	Air	0.0002	11.00	0.0023	g
		Total, g CO2 equivalents:		**9039.5505**	g

The most influential substance in global warming profile is carbon dioxide (CO_2) since it is released from almost all of the activities within airbag life cycle. In total, the largest contributor of CO_2 emission is from the use phase. During use phase, the largest emission is mainly from the combustion of fuel during the operation time of the car. As described earlier, the LCI data from VW Golf A4 was used as model for the use phase of the airbag.

The second largest contributor for global warming potential is Nitrous Oxide, N_2O. The main source of N_2O emissions is from the production phase. The N_2O emission is mainly come from the production of inflator component. The inflator is manufactured at Autoliv Romania (IRO).

The third largest source of global warming potential is methane, CH_4. The CH_4 is mainly emitted from the production phase, in which is production of cushion component.

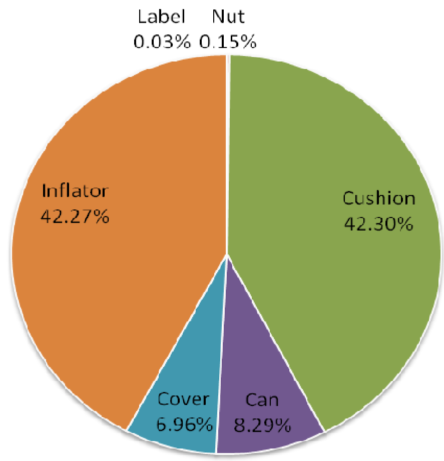


Figure 32. Global Warming Potential from Production Phase of Airbag Components

From production phase, the production of inflator and cushion share a notable portion of global warming potential (see Figure 32). Productions of inflator and cushion each contributes to 42% (around 3.8 kg of CO_2 equivalents) of global warming potential.

The included activities during use phase are mainly come from the emissions of fuel combustion. It is just only declared a small portion of included activities from maintenance, washing and production for replaced component. This gives reason to believe that not all the emissions have been inventoried and that the characterization result would give a higher value if the data had been more complete for the use phase.

On the other hand, the car that was used as a model for the use phase is has smaller in weight. It is also could give another reason to believe that the emissions for global warming will increase if the studied car, i.e. Volvo C30 that has higher number in weight, was used as a model.

The inflator and cushion are both two main component in the airbag module. Both of two components are using significant number of raw material, steel and polyamide respectively. Together with the transportation used since both two are produced abroad make inflator and cushion has the largest contribution in this characterization method.

8.2. Acidification

Emissions of substances responsible for acidification have been characterized and added as SO_2 equivalents. The sources of emissions are come from almost all activities within studied system. The results are shown in the table below.

Table 14. Acidification (max) of airbag, (CIT Ekologik, Index list May 2000), in g SO2 equivalent

Substance	Environment	Quantity	Factor	Result	Unit
Acid as H^+	Water	0.0500	32.0000	1.5992	g
H_2S	Air	0.0194	1.8800	0.0365	g
HCl	Air	0.1033	0.8800	0.0909	g
HF	Air	0.0075	1.6000	0.0120	g
HNO_3	Water	0.0000	0.5100	0.0000	g
NH_3	Air	1.0448	1.8800	1.9643	g
NH_4^+	Water	0.2324	3.5500	0.8250	g
NOx	Air	19.6742	0.7000	13.7720	g
SO_2	Air	25.9660	1.0000	25.9660	g
SO_x	Air	0.0185	1.0000	0.0185	g
		Total, g SO2 equivalents:		**44.2844**	g

The most influential substance in the acidification profile is sulphur dioxide, which accounts for 59% of the total amount in SO2 equivalent. The emissions of SO_2 mainly come from the manufacturing of inflator (around 52%, or 13.6 gr), mostly in the production of steel.

The second largest contributor for acidification potential is Nitrogen Oxides, NO_x. The main source of NO_x emissions is from the production phase. This is mainly come from the production of inflator component. The inflator is manufactured at Autoliv Romania (IRO).

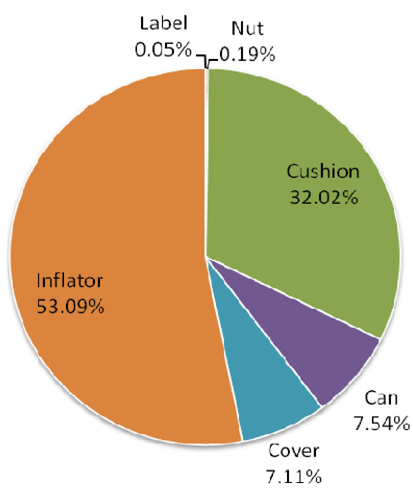


Figure 33. Acidification potential from production phase of airbag components

In the production phase, the production of inflator accounts for 53% of total acidification potential (23.5 g SO_2 equivalents), as shown in Figure 33. It is followed by production of cushion that accounts for 32% (14.2 g SO_2 equivalents) of total acidification potential from production.

In this study the steel production is represented by average steel production of European region. In fact, there are different types of steel that used for the material of airbag, i.e. carbon steel, stainless steel, and iron steel. So, if the site specific data was used, the results will slightly different.

The environmental load is quite dominated by the production phase and mainly from production of inflator. The main source of acidification gases emissions are mainly from production of steel. Therefore the component that has high of steel for the material, make them responsible for the large share of acidification potential. The other reason, steel is quite widely used so the average data for emissions from steel production is fully inventoried.

8.3. Eutrophication

Emissions of substances responsible for acidification have been characterized and added as NO_x equivalents. The results are shown in the Table 15 below.

Table 15. Eutrophication (max) (CIT Ekologik, Index list May 2000)

Substance	Environment	Quantity	Factor	Result	Unit
BOD, fossil	Water	0.0073	0.1690	0.0012	g
COD, fossil	Water	7.9463	0.1690	1.3429	g
HNO_3	Water	0.0000	0.7690	0.0000	g
NH_3	Air	1.0448	2.6900	2.8106	g
NH_4^+	Water	0.2324	2.5400	0.5903	g
Nitrates	Water	0.3042	0.7690	0.2339	g
Nitrogen	Air	2.6055	3.2300	8.4158	g
NO_2^-	Water	1.5236	1.0000	1.5236	g
NO_3^-	Water	0.0784	0.7690	0.0603	g
NO_x	Air	19.6742	1.0000	19.6742	g
Phosphate	Water	0.0390	7.6900	0.2998	g
PO_4^{3-}	Water	0.0384	7.6900	0.2953	g
TOC	Water	0.0365	0.6510	0.0238	g
Tot-N	Water	0.0262	3.2300	0.0846	g
Tot-P	Water	0.0000	23.5000	0.0000	g
		Total, g NOx equivalents:		**35.3563**	g

The most influential substance in the eutrophication profile by far is NO_x and followed by the emissions of Nitrogen. NO_x emissions and NO_2 are 19.67 g and 2.61 g respectively. These two gases emissions contribute to almost 80% of total eutrophication potential. The main component whose production emits the largest emissions of NO_x and Nitrogen is cushion.

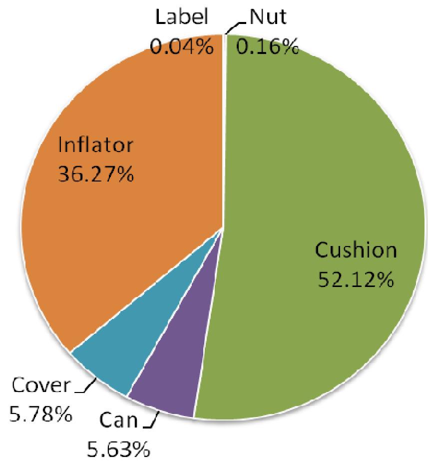


Figure 34. Eutrophication potential from production phase of airbag components

From production phase, the production of cushion accounts for 52% of total eutrophication potential (18.4 g NO_x equivalents), as shown in Figure 34. It is followed by production of inflator that accounts for 36% (12.8 g NO_x equivalents) of total acidification potential from production.

The production of polyamide for the cushion is the main source of emissions for eutrophication potential (7.2 g of NOx). The production of polyamide is accounted as the single process that emits the largest contribution for eutrophication potential. The main source of eutrophication gases emissions from production of inflator is mainly from steel production (4.3 g of NOx).

The data for production of raw material production differ a lot between sources. Sometimes, not all emissions are accounted in life cycle inventory data. It gives a reason to believe that the characterization result for eutrophication potential would give higher value if the data had been more complete. As for example, the emissions from production of gas generant are mainly from electricity consumption and from material production. It was caused by the difficulty to find the site specific data and confidentiality issue.

The environmental load is quite dominated by the production phase and mainly from production of inflator and cushion component. The single activity that can be pointed as the main source of eutrophication potential is production of polyamide. Polyamide has a big share in airbag module material (302.86 g), mostly for the cushion and also the thread. It consumes a lot of resources crude oil and natural gas for its production. The other reason, Polyamide 6.6 is quite widely used material so the average data for emissions from its production is fully inventoried.

8.4. Resource Depletion

Valuable resources can be exhausted to some extend by the production of any products and services. Resources predicted to be depleted by the manufacturing of airbag are listed below in Table 16.

Table 16. Resource depletion (reserve based) (CIT Ekologik, Index list May 2000)

Substance	Quantity	Factor	Result
Aluminium	0.8459	3.57E-14	3.020E-14
Bauxite	0.5933	1.19E-14	7.060E-15
Brown coal	228.9162	7.00E-16	1.602E-14
Coal	35.0926	7.00E-16	2.456E-14
Copper ore	0.0345	1.03E-14	3.549E-16
Cr	8.8771	1.68E-12	1.491E-11
Crude oil	5145.9299	8.09E-15	4.163E-11
Fe	134.9052	1.32E-14	1.781E-12
Hard coal, feedstock	753.8778	7.00E-16	5.277E-13
Iron-ore	2.3132	4.35E-15	1.006E-14
LPG	0.1230	9.15E-15	1.125E-15
Natural gas	804.1588	9.15E-15	7.358E-12
Peat	3.8567	7.00E-16	2.700E-15
Uranium (as pure U)	0.0513	5.96E-10	3.058E-11
	Total, g reservebase-1:		**9.703E-11**

Since the inflator consumes most of the steel resources and has largest electricity and energy consumption among others, it is reasonable to mention that inflator is affecting resource depletion more than the others. Inflator production is associated with around half of the total resource depletion for the production phase. The most affected material is crude oil (43%), used as energy source, lubricants, and raw material for several petroleum-based substances such as plastics and nylons. Other large resource depletion is for uranium and chromium, due to their relatively high factors.

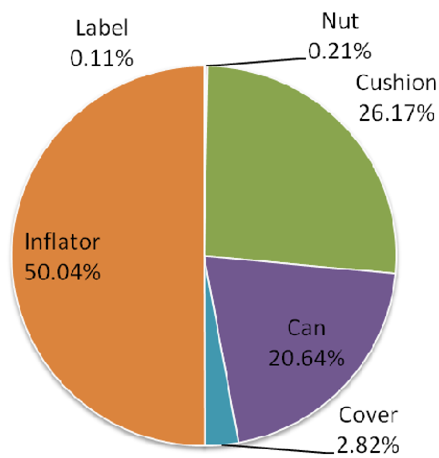


Figure 35. Resource depletion from production phase of airbag components

8.5. Aquatic Ecotoxicity

Emissions of substances responsible for aquatic ecotoxicity have been characterized and added. The results are shown in the Table 17; only emissions to water are included.

Table 17. Aquatic ecotoxicity (CIT Ekologik, Index list May 2000)

Substance	Environment	Quantity	Factor	Result	Unit
As	Water	3.724E-04	2.00E+06	0.745	m^3
Cd	Water	2.377E-04	2.00E+09	475.412	m^3
Cr^{3+}	Water	2.607E-05	1.00E+07	0.261	m^3
Cu	Water	1.000E-03	2.00E+07	21.995	m^3
Ni	Water	2.682E-02	3.30E+06	88.492	m^3
Oil	Water	1.235E-01	5.00E+05	61.766	m^3
Pb	Water	1.520E-03	2.00E+07	30.404	m^3
Phenol	Water	4.094E-03	5.90E+07	241.531	m^3
Zn	Water	5.762E-03	3.80E+06	21.894	m^3
Total, m^3 polluted water equivalents:				**942.50**	m^3

Cadmium is the biggest emission that contributes to aquatic eco-toxicity. During airbag life cycle, cadmium is mainly emitted from production phase. Steel production is the main sources of cadmium emissions, mainly for producing the inflator. The largest contributor for the aquatic toxicity in mass is nickel. The sources of emissions for nickel are come from production of steel for the inflator's material.

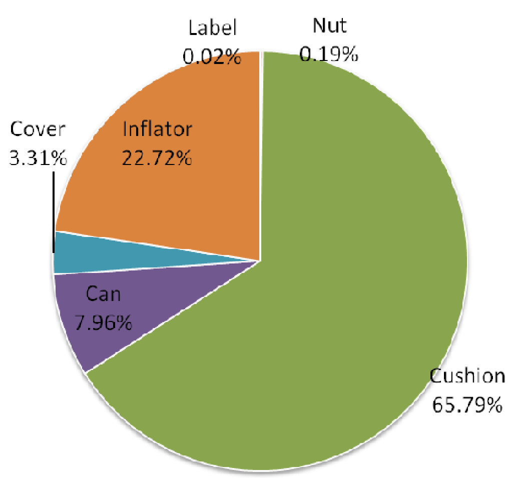


Figure 36. Aquatic ecotoxicity from production phase of airbag components

The activity that contributes to aquatic toxicity is mainly from production of polyamide 6.6 for the cushion, which emits cadmium and phenol. Steel manufacturing in inflator production generates cadmium and nickel. In addition, the electricity generation and zinc production contribute to aquatic eco-toxicity. All of the activities above contribute to almost all cadmium emissions during the airbag life cycle.

The site-specific data differ quite much when it comes to accounted water emissions. At many of the sites water emissions are not accounted for at all. This gives reason to believe that the characterization result would give higher values if the data had been more complete. The substances accounting for the largest contributions to this characterization method have all their main sources in the production of steel for production of the inflator.

8.6. Human Toxicity

Emissions of substances responsible for human toxicity have been characterized and added. The results are shown in the Table 18 below.

Table 18. Human toxicity indicator of airbag (CIT Ekologik, Index list May 2000)

Substance	Environment	Quantity	Factor	Result	Unit
As	Air	0.0004	4700.00	1.7504	g
Benzo(a)pyrene	Air	0.0000	17.00	0.0000	g
Cd	Air	0.0002	580.00	0.1379	g
CN^-	Air	0.0009	0.67	0.0006	g
CO	Air	10.2633	0.01	0.1232	g
Cr	Air	0.0900	6.70	0.6032	g
Cu	Air	0.0011	0.24	0.0003	g
Dioxin	Air	0.0000	3300000.00	0.0072	g
Fe	Air	0.4632	0.04	0.0195	g
HF	Air	0.0075	0.48	0.0036	g
H_2S	Air	0.0194	0.78	0.0152	g
Hg	Air	0.0001	120.00	0.0146	g
Mn	Air	0.0037	120.00	0.4396	g
Mo	Air	0.0064	3.30	0.0211	g
Ni	Air	0.0268	470.00	12.6033	g
NO_x	Air	19.6742	0.78	15.3459	g
PAH	Air	0.0005	17.00	0.0088	g
Pb	Air	0.0015	160.00	0.2432	g
Phenol	Air	0.0041	0.56	0.0023	g
Sn	Air	0.0002	0.02	0.0000	g
SO_2	Air	25.9660	1.20	31.1592	g
SO_x	Air	0.0185	1.20	0.0223	g
Toluene	Air	0.0020	0.04	0.0001	g
V	Air	0.0015	120.00	0.1857	g
Zn	Air	0.0058	0.03	0.0002	g
		Total, g contaminated bodyweight equivalents:		**62.7073**	g

Sulfur dioxide, nitrogen oxides and nickel are the substances that contribute the most to human toxicity in the production phase of airbag module's life cycle. All three of them are emitted mostly during the production of inflator. The large amount of emissions of carbon monoxide from the use phase is significant, but it has a lower weighting factor compared to the three substances.

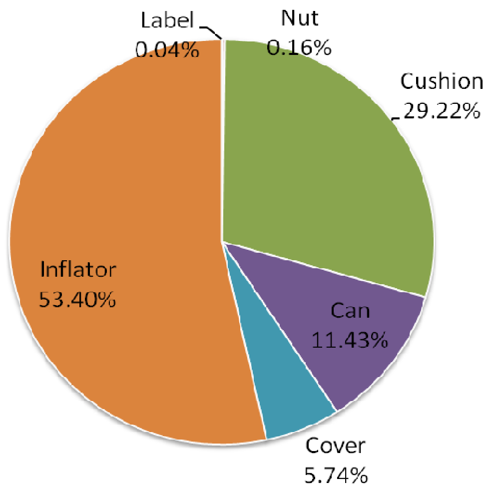


Figure 37. Human ecotoxicity from production phase of airbag components

Though not perceived as a highly toxic substance, sulfur dioxide has a high toxicity value in the airbag life cycle system because of the large amount of emissions. The emissions of sulfur dioxide, as explained earlier, come mostly from steel manufacturing (7.1 g), followed by production of Polyamide 6.6 for the cushion (7.0 g) and electricity generation (5.6 g). Virtually all of Nickel emissions (0.026 g) and a large part of NO_x emissions (4.4 g) are from steel manufacturing. See Figure 37.

The activity that contributes to aquatic toxicity is mainly from production of steel for the inflator. In addition, the electricity generation and zinc production contribute to aquatic eco-toxicity. Both of three activities above contribute to almost all Cadmium emissions during the airbag life cycle. In fact of another heavy and toxic substances emitted from these activities, it has less significance.

The site-specific data differ quite much when it comes to accounted air emissions. At many of the sites water emissions are not accounted for at all. This gives reason to believe that the characterization result would give higher values if the data had been more complete. The substances accounting for the largest contributions to this characterization method (SO_2, SO_x and nickel) have all their main sources in the production of steel for production of the inflator, followed by production of polyamide 6.6 for the cushion.

9. Analysis

9.1. Dominance Analysis

9.1.1. Key Processes

The environmental impact that can be associated to airbag can be divided according to the airbag life cycle, which is started from production (raw material extraction, component manufacturing, and assembly), use, and end-of-life phase. Below is a bar chart showing the contribution of each phase to the total environmental impacts that can be associated to one airbag (Figure 38).

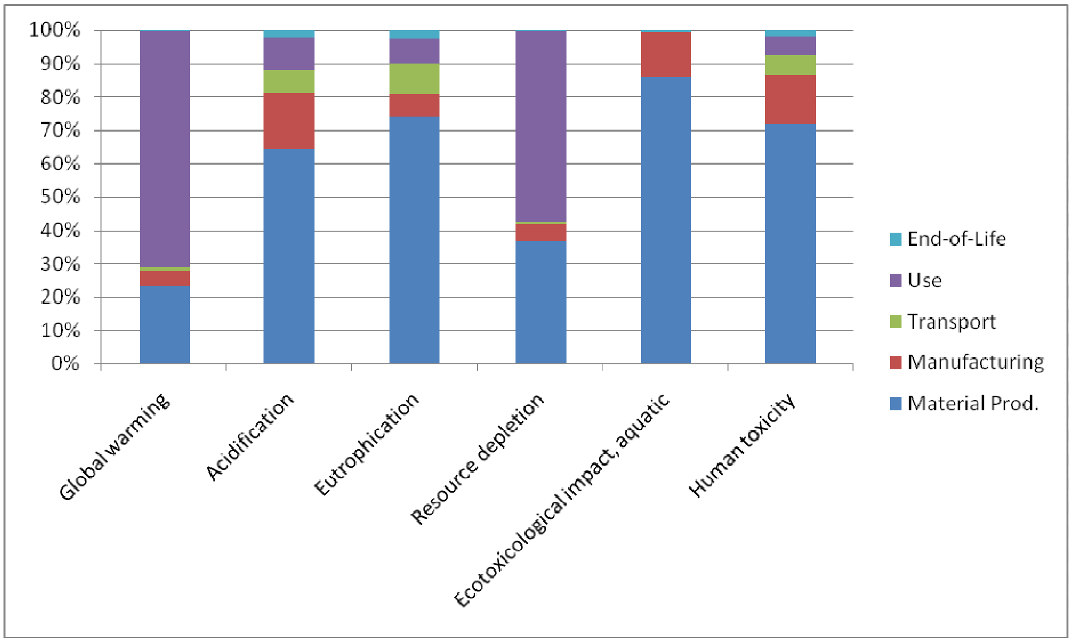


Figure 38. Environmental Impacts of an Airbag, Divided Per Phase

Production phase entails raw material production, component manufacturing, and associated transport. It has a wide range of emissions, in relatively large amounts. Therefore, it is the main contributor for acidification, eutrophication, ecotoxicological impact, and human toxicity. However, the use phase uses more non-renewable fuels and emits more carbon dioxide. Thus, it is the largest contributor for global warming and resource depletion. The contribution from the end-of-life phase is generally small compared to the other two phases.

Below are some selected processes from the production phases with high environmental impacts.

Steel production
Steel is a major substance of the airbag and has an even larger contribution to some emissions, including CO_2, SO_2, NO_x, nickel, lead, and zinc.

Polyamide production
Polyamide 6.6 is a major material of the airbag (mostly in cushion) and has a large contribution to some emissions since it made from crude oil, most notably carbon dioxide, methane and SO2.

Electricity generation
Electricity generation profile is quite varied among different countries, and is further complicated by the export and import of electricity to and from neighboring countries. For the sake of simplicity, the analysis in this LCA study takes the average domestic electricity generation for each country in question. The emissions from the electricity production are substantial, reflecting the energy intensive processes involved in manufacturing airbag components.

Transportation
Materials and components that constitute the final product of an airbag come from different countries in the world. The cushion is produced in Portugal, cover in Germany, and initiator is assembled in the Autoliv facility in the United States, using both domestic and imported materials. Though mostly light weight, the distances of substance and component transportation could be quite large, encompassing different continents. In average, the share of transportation phase during airbag module production is around 10% in maximum. The highest share is in eutrophication impact and mainly come from transportation during the inflator production.

9.1.2. Key Substances

Carbon dioxide
Carbon dioxide, the most common of greenhouse gases, contributes to global warming and climate change. Even though its global warming potential is far less strong than e.g. methane and nitrous oxide, the amount of CO_2 emissions in the airbag life cycle far exceeds the other substances. The contribution of each phase is shown in the graph below (Figure 39).

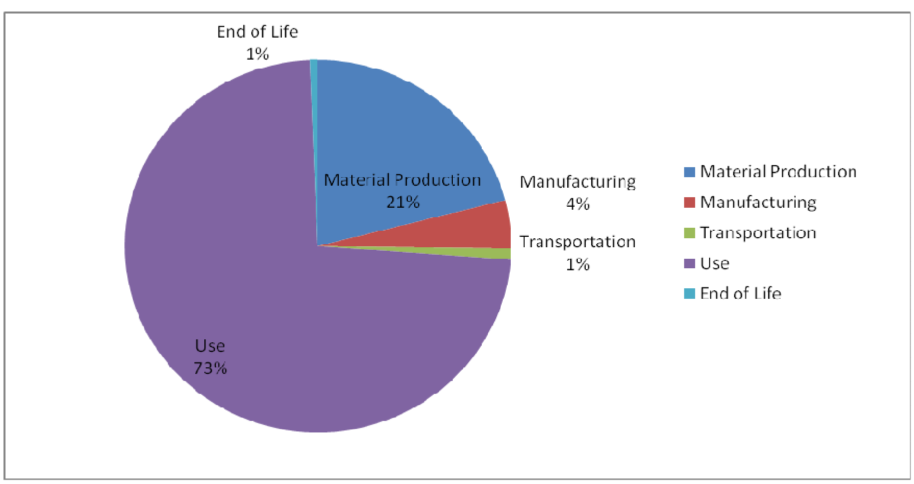


Figure 39. Total Emissions of Carbon Dioxide

Throughout the life of an airbag, the largest emission comes from the use phase (22.5 kg/unit airbag or 73% of total emission), when the airbag does not change at all and is just being carried around inside the car, under the steering wheel, contributing to fuel consumption. It is seems to be expected before, since in automotive industry the use phase is the most significance source of global warming potential. The use phase is based on the Life Cycle Inventory study of use phase from VW Golf A4 in which are assumed to be 10 years of operation time in European based region.

SO_2

Sulphur dioxide contributes to acidification and human toxicity. The largest contribution comes from polyamide production (7.0 g/unit airbag, or 24% of total emissions). See Figure 40 below.

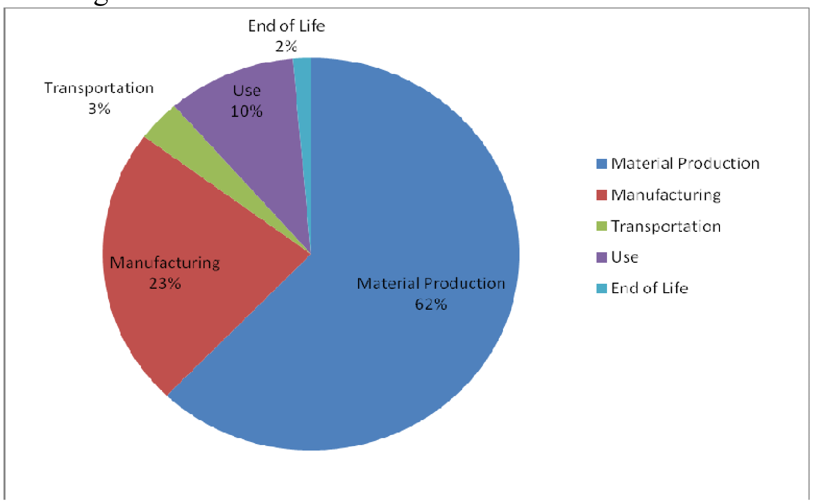


Figure 40. Total Emissions of Sulphur Dioxide

Methane

Methane also contributes to global warming, though the emissions are much less than carbon dioxide. Largest emissions come from the production of polyamide 6.6 for the cushion (6.1 g/unit airbag or 61% of total emissions). See Figure 41 below.

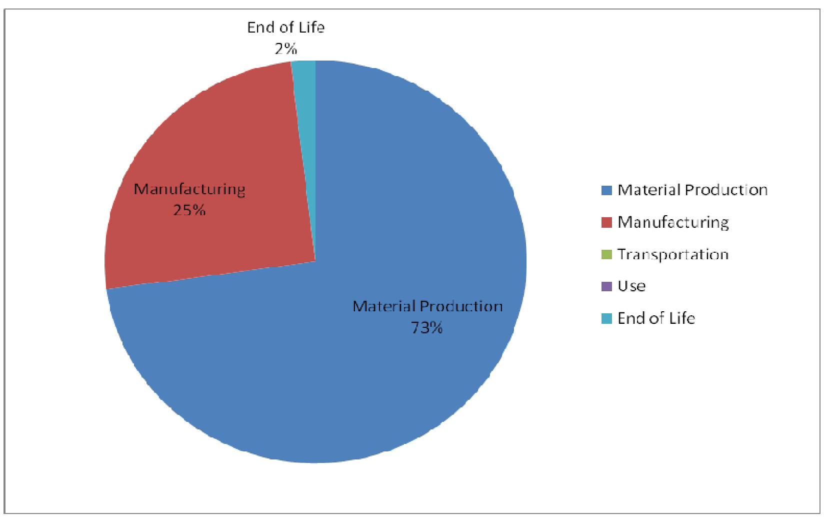


Figure 41. Total Emissions of Methane

NOx

Nitrogen oxides is the common term that groups together the nitrogen-oxygen compounds, including nitric oxide (NO) and nitrogen dioxide (NO_2). The compounds contribute to global warming, acidification, eutrophication, and human toxicity. Aside of the transportation (15%) and use phase (12%), the dominant process for NO_x emissions is steel production (4.44 g/unit airbag, or 19%). See Figure 42 below.

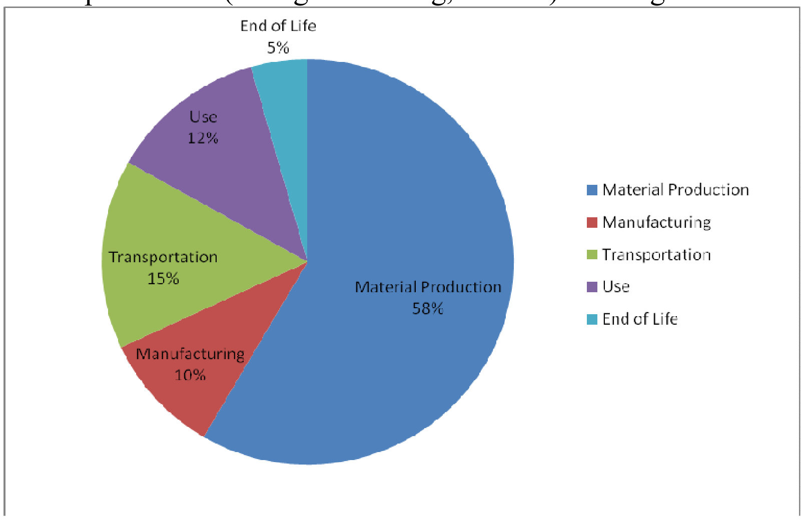


Figure 42. Total Emissions of Nitrogen Oxide

Zinc

Zinc shares a large portion of toxicity in airbag life cycle. It is used as metal coating for many components in airbag module, i.e., can, snap-in pinne, nut, and inflator. The sources of toxic emissions in form of cadmium, copper, lead and zinc. These emissions are mainly released during zinc production processes. As for comparison, producing 1 gram of zinc may cause 4.5 m^3 of aquatic toxicity while for the same amount of mass to produce steel and aluminum it only causes aquatic toxicity of 0.08 m^3 and 0.164 m^3 polluted water respectively.

Cadmium

Cadmium is emitted in trace amounts during electricity generation and steel manufacturing, and contributes to the human toxicity feature of the airbag life cycle. Though previously used in steel plating, its application in industry has been limited to Ni-Cd batteries due to its high toxicity.

Nickel

In the life cycle of the airbag, nickel emissions amount to 0.15 gram/unit airbag, exclusively from steel production, due to nickel content in the steel scrap and metal ores. Nickel contributes to human toxicity for being allergenic, carcinogenic, and toxic.

Lead

Lead has been realized as being harmful to human, and its use has been phased out from many applications. However, small amounts of lead (27 mg/unit airbag) are still emitted from steel production processes.

9.1.3. Energy Consumption

The life cycle of a unit of airbag module consumes 569.56 MJ of energy. The most energy consuming phase is use phase, consuming fuel that equals 454.17 MJ worth of crude oil. The most energy intensive process from production phase is production of steel for material of can and inflator. The second largest energy consuming process of the production phase is the production of polyamide 6.6 for the cushion.

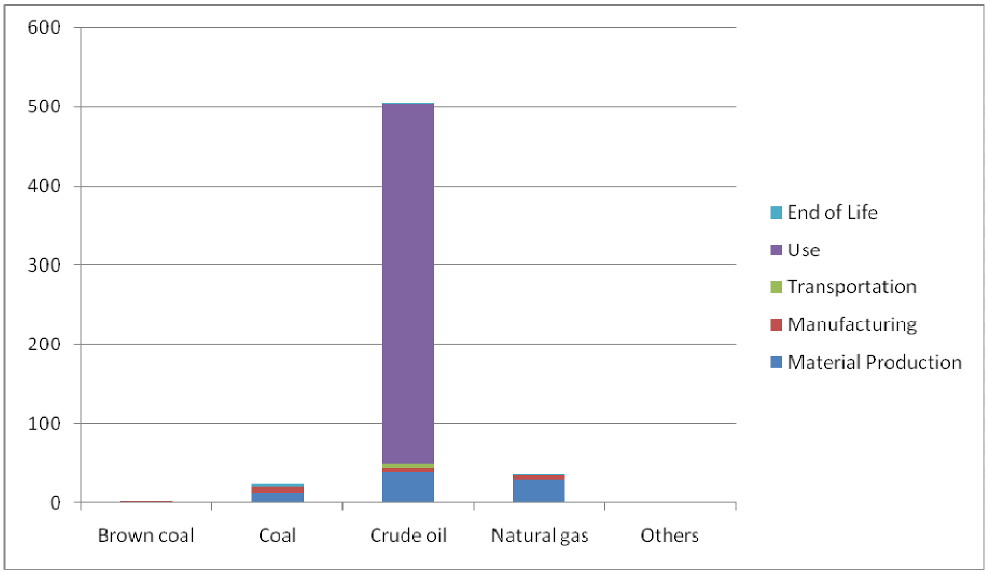


Figure 43. Energy Consumption during the Life Cycle of An Airbag

Figure 43 shows that natural gas (36.73 MJ) and hard coal (24.53 MJ) is the second and third largest types of energy consumed by the airbag module. The hard coal is mainly consumed by inflator and cover, while natural gas is mainly consumed by the production of cushion.

9.1.4. Water Consumption

The whole airbag life cycle also consumes 79.24 kg of water, or around 53 times the weight of an airbag. The largest water-consuming process is inflator production, consuming 56.63 of water per unit airbag. See Figure 45.

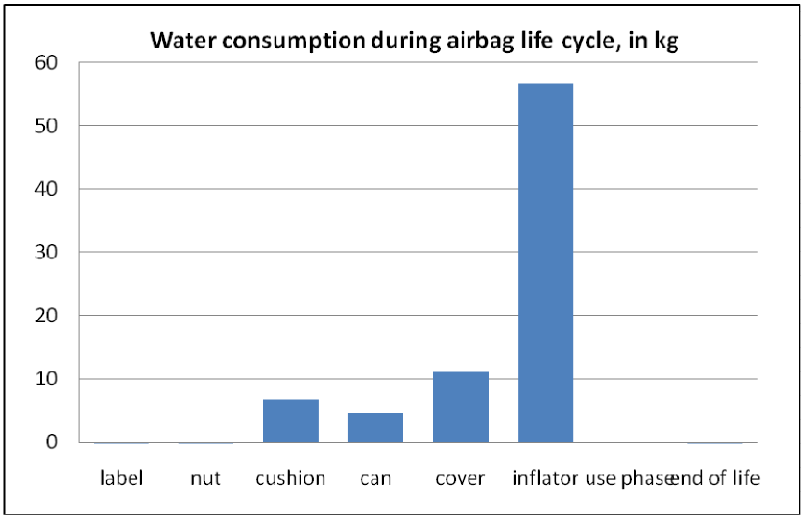


Figure 44. Water Consumption during the Life Cycle of An Airbag

Electricity generation (45.47 kg) and steel production (10.92 kg) for producing the inflator are the activities that contribute a large portion of water consumption. This is mainly caused that to produce the inflator, there are large number of small components and therefore has many steps processes.

9.1.5. Total Wastes

Wastes have been reported both as elementary (no further treatment necessary) and non-elementary (further treatment necessary). Most of the waste reported needs further treatment and are therefore sorted under the non-elementary waste category.

Elementary waste
The production and manufacturing of cover causes the most elementary waste. Exactly what this is caused by is hard to say since the most of this non-elementary waste has been inventoried as "other waste" or "unspecified waste", but mainly is in types of polymer. The component making the largest contribution is the cover.

Non-elementary waste
The non-elementary waste is by far the largest waste category. Here everything is included no matter what waste treatment is needed. The production of inflator is the largest contributor since inflator has large number of process activities to produce the inflator. It should be noted that almost all of this waste is waste in deposit or mixed industrial waste.

The total waste production from airbag life cycle can be seen at Figure 46.

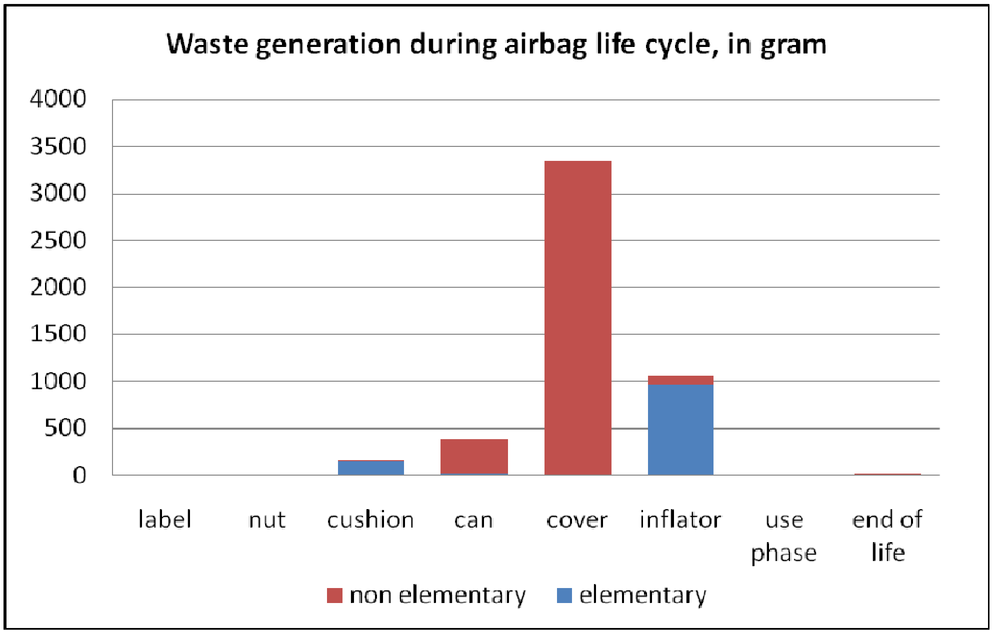


Figure 45. Waste generation from the life cycle of airbag

9.2. Comparison between Airbags and A Complete Car

As an airbag is not a consumer product by itself, its environmental indicators will be more comprehensive when compared with the final product: an automobile. This study includes such comparison between airbags and a complete car. The emissions data for a complete car was derived from an LCA conducted by Schweimer (Volkswagen AG) and Kevin (University of Kassel), both on VW Golf A4. Data on resource use and emissions are available on Appendix l.

The airbag in this study is actually installed in Volvo C30. However, there is a lack of literature for LCA studies on Volvo C30. VW Golf A4 is a good approximation of Volvo C30 because both are in the same class of car, i.e. small family car. Both also have similar weight: 1,330 kg (Volvo C30) and 1,181 kg (VW Golf A4). Below are described the comparison between airbags module and a complete car from each of life cycle phase.

It was assumed there are 10 airbags inside a car, i.e. driver airbag, passenger airbag, two side curtain airbags, two knee airbags, and four seat mounted airbags. The total weight for ten airbags is 15.6 kg (about 1% of the car weight). The resulted environmental impact for the studied airbag was then multiplied by ten factors to gain the environmental impacts for all the airbags inside a car.

Table 19. Comparison of environmental impact airbags and a complete car

Impact categories	Complete Car	Airbags
Global warming, kg CO_2 equivalents	4,583.27	31.58
Eutrophication, kg NO_x equivalents	9.55	0.04
Acidification, kg SO_2 equivalents	15.21	0.05
Aquatic ecotoxicity, m3 contaminated water	4407.30	947.73
Human toxicity, kg contaminated bodyweight	11.0740	0.07

Looking at the results presented above it is clear that the airbag accounts for about two percent for most of environmental impacts of a complete car (Table 19). It seems to be reasonable results compared to LCA study done in automotive industry like LCA done by Finkbeiner (2006) on environmental certificate of Mercedes Benz S-class, where the steering wheel contributes to around 2% of total CO_2 and SO_2 emissions.

9.2.1. Production Phase

In a car system, the main source of emissions is steel production for the chassis and body. In an airbag, the main sources of environmental impacts categories are dominated by production of inflator and cushion. More specifically, the production of steel and production of polyamide contribute the most global warming potential. See Figure 44 below for the contribution of airbags to the environmental impacts of a car.

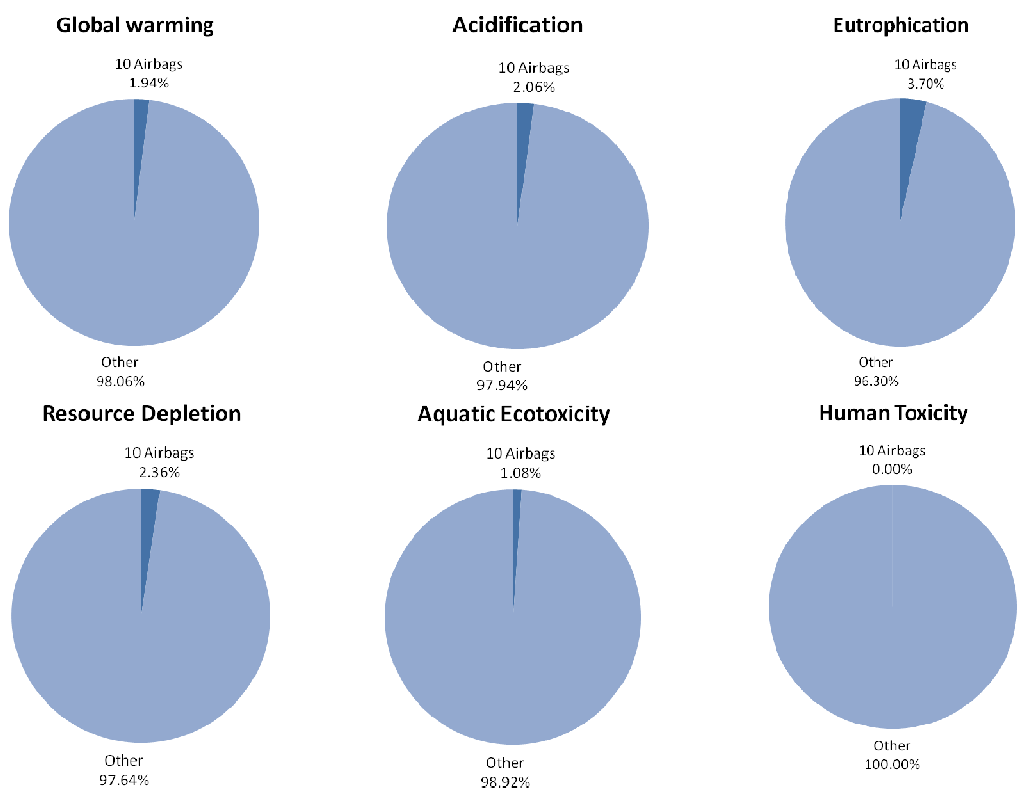


Figure 46. Environmental impact of airbags compared to a complete car from production phase

9.2.2. Use Phase

Looking at the results presented figure below it is clear that the airbag accounts for mostly less than 1 percent for most of environmental impact of complete car (Figure 48). Compared to the production phase, the environmental impacts during use phase are less important. The main reason is that the considered emissions during the use phase are only emissions that are directly associated to the weight contribution of airbags to the fuel consumption.

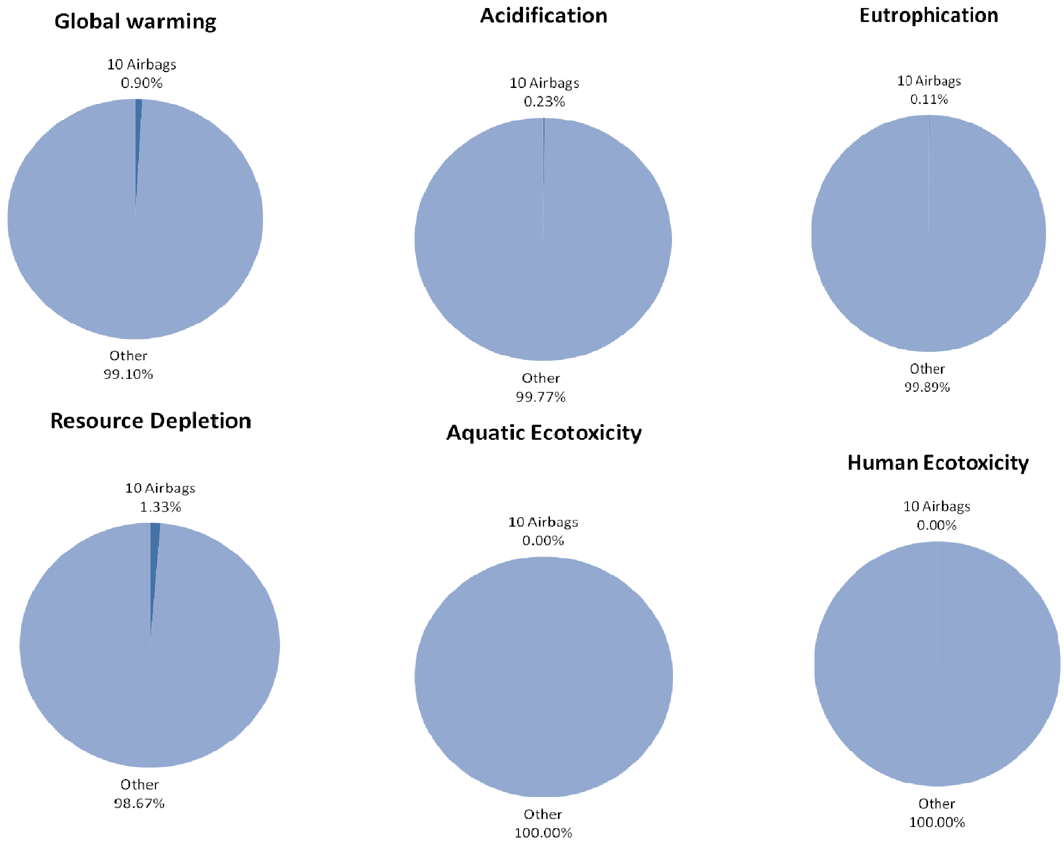


Figure 47. Environmental impact of airbags compared to a complete car during the use phase

The emissions like COD and BOD were not included since from the report, it was said that above emissions are coming from washing and maintenance of the car. The considered emissions just only generated from the increasing fuel consumption of the car caused by the increasing weight of the car since presentences of the airbags inside. The result was slightly different if the cars have accident during the use phase.

It can also be seen that the ecotoxicological impact of airbag during use phase is very small, near to zero. The reason is that there are no any emissions generated directly from fuel combustion that contaminate to water. Most of the emissions are released to air. The considered emissions are CO_2, CO, NO_x, SO_2, hydrocarbon and particulate matter. Larger percentages come from production phase, while in the use phase and end-of-life the contribution of airbag system is even less.

9.2.3. End of Life

Almost the same figure as use phase above, end of life chare of airbags is around one percent of total environmental impact categories for a complete car (Figure 49). The emissions during the end of life of airbag module come from the gases that emitted during the deployment of the airbags inside the car. The others are mainly from the share of environmental emissions from the shredding process, sorting, landfilling and incineration. In this end of life phase, the gases emitted from the deployment of airbags are less significant compared to emissions from shredding process, except for eutrophication because of the large emissions of nitrogen gas during airbag deployment.

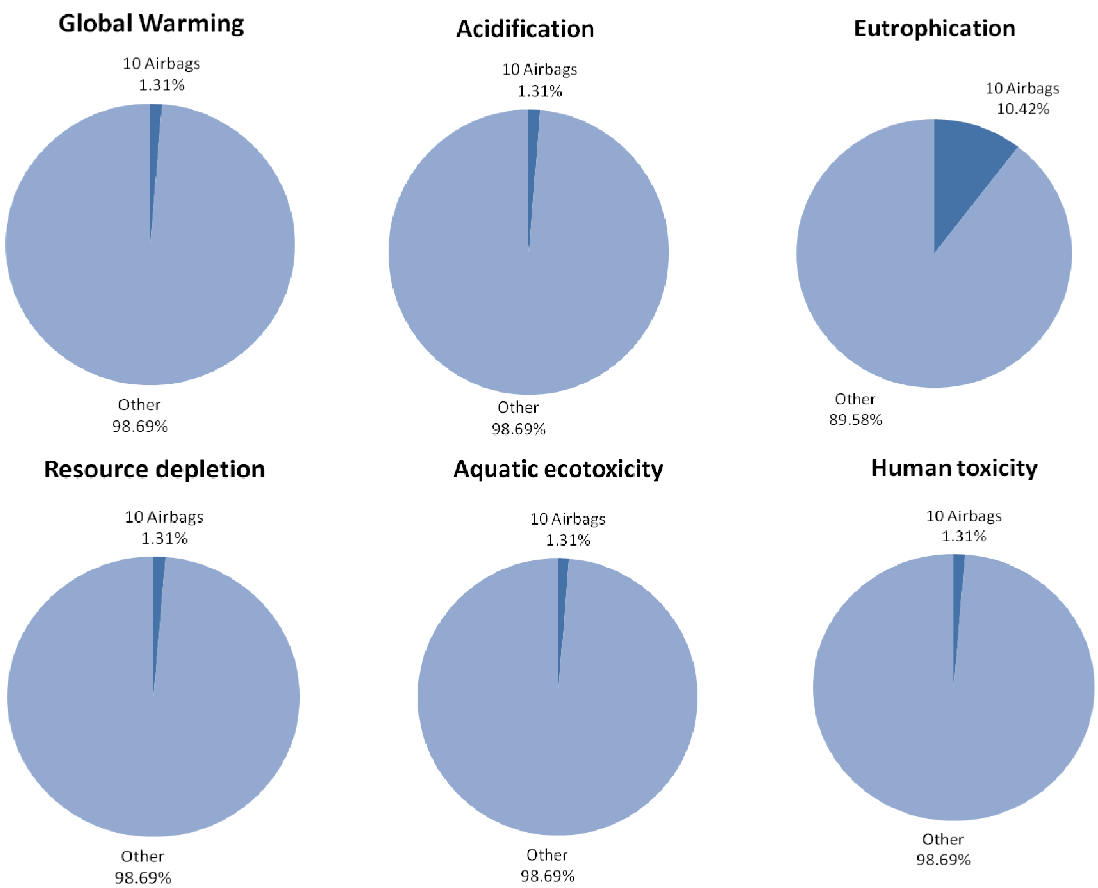


Figure 48. Environmental impacts of airbags compared to a complete car during end of life phase

10. Discussion

The calculations in this project are based, as much as possible, on site-specific data. The sources of data have been remarked in Chapter 6 under the discussion of each main component. A quantitative summary is presented in the following section on data quality. Later this chapter, we will discuss some assumptions used in calculations. They are partly based on discussion with suppliers, which revealed general procedures in waste management and logistics as commonly practiced in the industrial business. Some other assumptions can actually be considered to belong to generic data, because they are derived from statistical average numbers. References on e.g. distance measurement are also mentioned. The final section is devoted to the discussion of an alternative scenario for the end of life phase.

10.1. Data Quality

Most of the manufacturing data used in this study is first-hand quantitative data supplied by people within the production, quality, and environmental departments. Site-specific data represent 71% from the total 56 manufacturing processes. Average (generic) data have a share of 25%, mainly for the production of the label, cover, and some of cold drawing processes. Estimations have been made in this study and have a share of 4% of total manufacturing processes. These estimations are mainly done for replacing the data for manufacturing of gas generant due to the confidentiality issue.

Raw material acquisition data as far as possible are traced to the suppliers, but in fact most of the suppliers for raw material extraction needed a long time to discover and it would also be difficult to collect the data for emissions from their processes. Hence, the average data were then used and seem to be able to represent more detailed and comprehensive information for emissions, material and energy inputs and description of the processes included. In this raw material extraction phase, average data represent around 88% of total 50 raw materials. The rest (12%) are estimated mainly for production of gas generant for the inflator.

By the above information, the uncertainty level and the weakness point of this study are discovered. From total 6 components of the airbag module, the lower uncertainty levels are showed by the data results for production of cushion, nut, can and inflator. The results can be used as basic information for future research and development. The label and cover are two main components with higher uncertainty. These were caused by difficulty in getting the response from the suppliers since the company has chaotic situation caused by the global economic recession. Despite of the higher uncertainty level, the general data used produce a results that seems to be reasonable compared to the other components in the airbag module system.

The proportion of site-specific data versus generic data as explained above, and those two types of data versus assumptions, might pose a problem in supporting the reliability of calculation results. In the initial phase of the project, there was a spirited effort to track all branches of the life cycle flowchart. Later in the work, it was realized that the ambition was not only unattainable but also risky. Even if we were to devote more time on the project and obtained higher quality raw data from contacts, this might not produced the desired improvement. While tracking further from the gate to the cradle, the contribution of each process to overall data quality will diminish. Insistence on site-specific data might even result in a certain degree of anomaly in case of multiple suppliers, in which a raw material or component is supplied by more than one suppliers due to price competitiveness and procurement security. Site-specific data would not then be representative of the actual material flows. In such cases it is then preferable to use generic data.

10.2. Assumptions

Assumptions are made in the calculations when site-specific data are not available. These are discussed below.

10.1.1. Transportation

Sub-suppliers' identity is confidential in some cases, which made it difficult to get site-specific information on transportation route and distance. In some other cases, suppliers do not have an established route and continually search for the most economic way to transport their products to customers. Yet some others mentioned that they used heavy trucks eventhough the logistic involves points in close distance, more normally served by small trucks. Therefore, it is necessary to make assumptions regarding transportation modes and routes.

Within this study, land transportations are assumed to use long-distance trailer trucks, with a payload capacity of 40 tones and energy requirement of 0.65 MJ/ton.km. Emissions follow the emission regulations for vehicles manufactured later than 2000 (Euro 3). This represents the normal scenario in transportation system today in Western Europe and the United States. The transportations in this study take place mostly in Europe and US, not Asia or other regions. Euro 3 was chosen because the data is available from (Baumann & Tillman, 2004), excerpted from the data compiled by the Swedish organization of Network for Transport and Environment (Nätverket för Transporter och Miljön, NTM).

A previous LCA thesis at Chalmers used Euro 0 standard for transport emissions (Ekdahl, 2001). However, Euro 0 does not regulate CO_2 emissions (only CO, HC, NO_x, and PM). The authors of this report believe that it would be better to use the same numbers across emissions including CO_2, so Euro 3 was used instead. An Italian logistic company (2006) reported the composition of their fleet as follows: Euro 0 (2%), Euro 1 (6%), Euro 2 (33%), and Euro 3 (59%). If this company could represent the EU and American logistics, then the assumption of 100% Euro 3 would not have a large error margin. Depending on the point of view, this might be a closer estimation than following the percentages above. The Euro standard regulations are for newly-produced cars (e.g. earliest Sep 2009 for Euro 5) and the logistic companies typically would not have large portions of Euro 4 (Jan 2005) and Euro 5 in their fleet, as shown by the company above.

Routes and distance between points located in the Western European countries and United States are calculated using Google Maps. The actual route (and thus distance) may be different.

Water transportations use large ships with energy requirement of 0.216 MJ/ton.km. Transportations of components to Autoliv Romania in Brasov from suppliers across the Pacific Ocean are by ships sailing between New York, the United States and Constanta, Romania. Other ports along the Atlantic coast of US have roughly the same distance with the Continental Europe.

Transportation emissions data are based on the average transportation data compiled by the Network for Transport and the Environment (NTM), 2002, and presented in Baumann & Tillman (2004). More comprehensive data are available at the NTM website (http://www.ntm.a.se) by free registration.

10.1.2. Electricity Generation

Inventory for electricity production systems is based on "Environmental life cycle inventoried of energy systems" by Frischknecht et al (1996) as presented in Baumann & Tillman (2004).

Data for electricity generation for each process is based on the average of the home country. Data for France, Germany, Italy, Sweden, the United Kingdom, and the United States are for 1998, by International Energy Agency (2001). Data for those countries are also available for year 2006 from the IEA website, but "Hard coal" and "Lignite" are grouped under "Coal". Hard coal and lignite have quite different emissions profile. For better accuracy in emissions calculation, it was decided to use the 1998 statistics. Data for Romania, the Czech Republic, Mexico, Turkey, Portugal, and the Netherlands are for 2006, also from IEA. Data for Taiwan were obtained from the Energy Statistics Handbook 2008, published by the Bureau of Energy, Republic of China.

10.1.3. Steel Production

Life cycle inventory for all steel components used the inventory data for stainless steel production mainly for components where manufactured in Europe, supplied by the European Confederation of Iron and Steel Industries to the European LCI database. For steel where produced in Taiwan for example, the global average data on steel production was used. The use of site-specific data on different types of steel production will change the results in some cases.

10.1.4. Polyamide 6.6 Production

Life cycle inventory for polyamide 6.6 components used the inventory data for polyamide 6.6 fibers production, supplied by the Association of Plastics Manufacturers in Europe to the European LCI database. The use of site-specific data on polyamide 6.6 production will change the results in some cases.

10.1.5. Gas Generant Production

Due to confidentiality issue, the suppliers had negative response to request of data on the production of gas generant. The life cycle inventory data for gas generant is mainly from production of its raw material, i.e., urea and ammonium nitrate from US Life Cycle Inventory data. For this reason, it is reasonable to mention that the characterization result for airbag mainly for inflator will be higher than presented in this LCA study.

10.1.6. Waste Management and Recycling Practice

Wastes in general are not easy to quantify due to allocation problem. Companies typically have a waste management company collect their wastes, without detailed documentation on the types and amounts of wastes. The figures presented in this study are obtained from life cycle inventory data.

In certain industries such as textiles, recycling is an established practice and virtually all scraps are recycled. These recycled materials are beyond the scope of this study. It is interesting to note that companies that responded most favorably to this project and provided the most complete information are also those that are most dedicated to environmental practice in general, including recycling.

10.2. Alternative Scenario for the End of Life Phase

As mentioned previously in the discussion on the end of life phase (see Section 6.11), the studied airbag is assumed to be deployed inside a car before shredding. Figure 50 below shows a comparison of emissions between that scenario and an alternative, wherein the airbag is dismantled and sent back to Autoliv. In the second scenario, the dismantling facility is assumed to be located in the middle part of the United States, representing the worldwide distribution of waste management facilities.

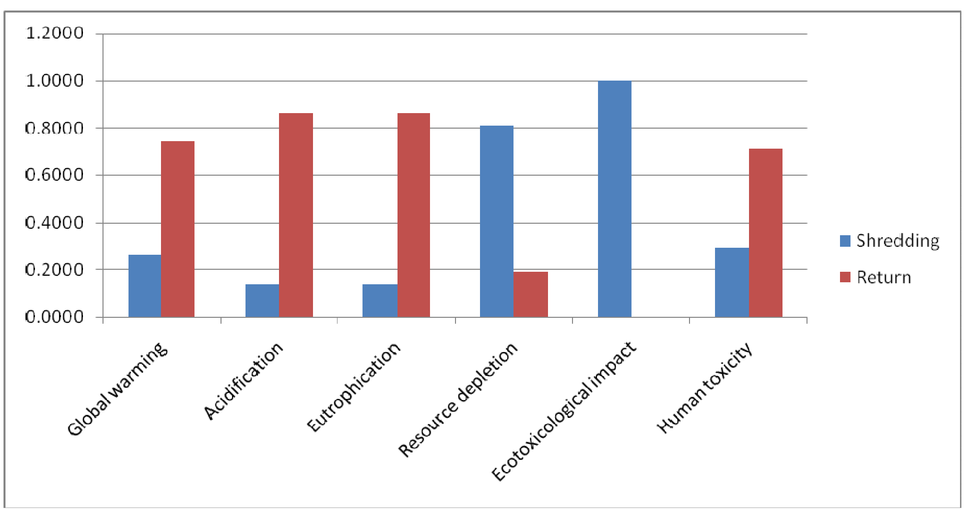


Figure 49. Environmental Impacts of Two End of Life Scenarios

The second scenario, dismantling, seems to perform worse because it entails long-distance transportation. The fuel consumption associated with the long transport results in high CO_2 and NO_x emissions, thus giving a high impact in global warming, acidification, eutrophication, and human toxicity. On the other hand, the shredding consumes a high amount of energy and results in emissions of several toxic compounds, thus performs worse in terms of resource depletion and ecotoxicological impacts.

It should be noted that the parameters are calculated only by taking the shredding and the return transportation into account. In case of return, the airbag will be disassembled and some components will be reused. This reuse practice might have competitive edge over material recycling and is worth studying in future studies by Autoliv.

11. Conclusions

In this chapter the results of the questions in goal and scope of this study, future potentials for LCA within Autoliv is investigated as well as suggestions for further work concerning data documentation.

11.1. Results

As previously mentioned in Section 1.2, the goal of this study is to investigate the environmental performance of Autoliv driver airbags production, from cradle to grave. The research questions as formulated from the purpose of the study (see Section 4.1) are answered below.

1. *What are the environmental impacts that can be associated with the airbag?*

   In this study, the environmental impacts that can be associated to airbag life cycle are global warming potential, acidification potential, eutrophication, aquatic ecotoxicity, human toxicity and resource depletion. The most critical sources of environmental impacts in the production phase are steel and polyamide production processes. However, viewed from cradle to grave, the use phase contributes to a large portion of environmental impacts, due to GHG emissions during fuel combustion in the car lifetime.

2. *Analyze different environmental impacts such as consumption of different resources, e.g. energy, water, materials, etc., emissions of specific pollutants such as CO_2, NO_x, SO_2, etc. and amounts of generated waste.*

   Life cycle of one unit driver airbag has the global warming potential equivalent with 31.78 kg of CO_2 equivalents, acidification equivalent with 50.43 g of SO_2, eutrophication equivalent with 39.35 g of NO_x, resource depletion of 1.52E-10 g reservebase^{-1}, toxicological impact to aquatic equivalents to 947.73 m^3 of water, and 67.78 g of contaminated bodyweight for human toxicity. The whole life cycle also generates 4.93 kg waste and consumes 79.24 kg water.

3. *Determine the relative environmental load of the airbag package compared to a complete car.*

   The environmental load of the airbag production system compared to a complete car is quite low, around 2% across several indicators of impacts. The shares are smaller for the use phase, but larger for the end of life phase, when the gases are emitted from airbag deployment. As a comparison, ten airbags weigh around 15 kg, or around 1% of a Volvo C30 car's total weight.

   This seems to be reasonable results compared with other LCA studies done in automotive industry like the LCA done by Finkbeiner (2006) on environmental certificate of Mercedez Benz S-class. In this study, the steering wheel is contributed to around 2% of total CO_2 and SO_2 emissions from car production. Another LCA study done by Subic (2006) on environmental impacts of seat in a car that shows the contribution of production phase of seat is 23% and use phase is 77%, which in this case is almost the same portion of environmental impacts, i.e., mainly from global warming potential, associated to airbag module.

4. *Determine whether there are materials in the product that should be avoided for environmental reasons.*

   Some materials in the airbag system should be avoided for environmental consideration, mainly in reduction weight of steel and polyamide content in airbag module. Other materials that should be avoided in matter of its toxicity are zinc for the coating of steel components. A shift to other material like aluminum-based components, which do not require zinc coating, would be beneficial because of lower environmental impacts during production phase and also use phase with its smaller weight compared to steel.

The results of this study correspond to those of a previous Autoliv internal study on airbag life cycle, as mentioned by consulted sources at Autoliv.

11.2. Further Studies

11.2.1. Life cycle inventory

The completeness of this LCA study is difficult to reach. The inventoried resources use, energy consumption, and emitted emissions are not always fully gained from the suppliers. This study needs more verification and deeper efforts to complete the life cycle inventory data. One effort can be done by using the licensed software since there are more complete and detailed available LCI data along with the software. By doing this, the result of environmental impacts that can be associated to the airbag module would be more precise and would be fair if In this it is compared to the others products, e.g., seat belt, night vision camera, electronic control unit and sensors.

11.2.2. Improvement Assessment

Despite of there are many limitations of this study in investigating the environmental impacts of the airbag module, there is possible improvement that could be suggested. One of the suggestions is by doing more research and development to reduce or replace the use of steel and or polyamide 6.6 to a material that has lower environmental impacts. A future LCA study can use this study as a basis knowledge to choose the material that can be used to reduce the environmental impacts associated to airbags.

11.2.3. Comparison

It is an interesting and challenging study which as the earliest study to investigate the environmental performance of safety equipments in a car. This LCA study has been used as basic model in conducting the other LCA and further be used as comparison for the rest of safety equipments product produced by Autoliv, i.e., seat belt, night vision camera, electrical control unit and sensors. The comparison results will give interesting information to get in deep of understanding and basic knowledge to do improvement for better environmental performances of vehicle safety equipment.

12. Potential Use of LCA within Autoliv

In this section the potential use of LCA studies within Autoliv is investigated and suggestions for further studies are given.

12.1. Research on Weight Reduction

With all the limitations of this LCA study, one of the suggested results is to keep in research on weight reduction. Since it will be significant reduce the environmental impact during production, transportation and mainly use phase. This LCA study can be used in a simple way as rule of thumb in airbag supply chain management. Furthermore, the LCI data could help as valuable basic reference to licensed LCA software and could help makes research and development processes on weight reduction become easier and takes less time to accomplish.

12.2. Internal System Update and Synchronization

The recent conducted LCA study by Autoliv in the running processes has found many mismatch information within Autoliv internal information system, e.g., AGPS, PLM and IMDS. The founded mismatches are ´mainly information concerning the databases of suppliers, material content and weight, etc. Further work could be conducted to synchronize these information to bring an easier and avoid miscommunication within department in Autoliv, suppliers and customers.

12.3. Suppliers and Customers Communication

Life cycle assessment study within company could have beneficiate in communicating the company's environmental efforts. By these recent LCA study, Autoliv should be more confidence in declaring their environmental concern of safety equipment system to their suppliers and moreover to their customers. In addition, it could increase the competitive advantages of Autoliv to compete and challenge the other supplier of vehicle safety equipment. In further cases, it can be used for comparison for environmental impacts caused by a complete car. By this way, the comparison study result can be used to inform the customers of the car to realize the importance of safety equipment in a car and at the same time, understanding the environmental impacts associated to it.

On the other hand, by managing a good communication between Autoliv and their suppliers, it could be more beneficiate if there is an agreement in future works between Autoliv and their suppliers to work together in developing better solution in performing sustainable development in automotive industry. As for example, these LCA study could be a good start to build a green supply chain management in vehicle safety equipment system.

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A. Appendix

A.1. Suppliers questionnaire

QUESTIONNAIRE TO SUPPLIERS

Life cycle inventory information

Master's Thesis - Life Cycle Assessment on Autoliv's Airbag
Driver Airbag, VOLVO P14 DAB EU VCC 8623349
Engineering Part 608178000E 02

Susetyo.Priyojati@autoliv.com
Arief.Mujiyanto@autoliv.com
+46 322 62 62 95

Company Profile

Company name	
Company address	

Contact Person

Name			
Position			
E-mail		Phone no.	

Monthly Energy Use

	Period	Amount	Unit
Electricity consumption			
Electricity bill			

Monthly Water Use

	Period	Amount	Unit
Water consumption			
Water bill			

Product Information

Part no.		Name:				
Production amount			Unit:		Period:	
Unit price					Currency:	
Buyer company						
Buyer address						

Production Process

Please provide a brief description of the production process.

Materials

Part no.	Title	Supplier	Supplier Contact	
			Name	
			Phone no.	
			E-mail	
			Name	
			Phone no.	
			E-mail	
			Name	
			Phone no.	
			E-mail	
			Name	
			Phone no.	
			E-mail	

Materials (continued)

Part no.	Title	Supplier	Supplier Contact	
			Name	
			Phone no.	
			E-mail	
			Name	
			Phone no.	
			E-mail	
			Name	
			Phone no.	
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Thank you very much for your support!

A.3. Materials not traced to the cradle

No.	Material	Weight (g)	Remark
1	Chromate film yellow Zn/ZnFe/ZnNi	0.05000	
2	Special metals, platinum/rhodium,	0.59600	
3	Passivation blue/transp. Zn/ZnFe/ZnNi	0.71520	
4	Nickel, alloy	1.19200	
5	Thermoplastic, PMMA	0.03000	
6	Glass Fibers	3.54000	
7	Screen printing ink/pad printing ink (cured)	0.00100	
8	Lacquer, thermal ink, black	0.01000	
9	Lacquer, YV-lak Flexo	0.10000	
10	Color Hydrokett 2000 (ink)	0.25000	
11	Compression sealing glass	0.59600	
12	Lacquer, Alexit, Decorlack 405-50	1.00000	
13	Ceramic paper	2.30000	
	Total	**10.3802**	0.66% of total weight

A.4. Special compounds

1. Acrylonitrile Butadiene Styrene (ABS)

Acrylonitrile Butadiene Styrene (ABS) is a group of thermoplastics polymers. The polymers combines the characteristics of each element, i.e. the resilience of polybutadiene, hardness of polyacrylonitrile, and rigidity of polystyrene. The products characteristic can be adjusted by changing the amounts of each copolymer, the length of the polymer chains, and the degree of interlinking.

ABS can be made by dissolving polybutadiene in liquid acrylonitrile and styrene monomers. The polymerization begins with the introduction of free-radical initiators. ABS can also be made in which polybutadiene is prepared as a watery latex and styrene and acrylonitrile are introduced and copolymerized. ABS was patented in 1948 and introduced to commercial markets by the Borg-Warner Corporation in 1954. (Encyclopedia of Britannica, 2009).

Hundreds of standard grades of ABS are available, including many special grades that are alloyed or modified to give different properties. The standard grades are rigid, hard and tough, and have good impact strength. ABS is regarded as a good engineering plastic and a common substitute for metals in structural parts. ABS in pellet form can be extruded, blow-molded, calendered, or injection-molded. ABS powders are used as modifiers for other resins, for example PVC (Encyclopedia of Polymer, 2009). Typical applications for ABS are household appliances, automotive parts, business-machines and telephone components, pipe and pipe fittings, packaging and shoe heels.

In the airbag module, ABS is used as a hard part, i.e., the inside of cover and in the emblem. In this study, ABS also replaced TPS-SEBS (Thermoplastics Styrene - Styrene Ethylene Butadiene Styrene), since both polymers have almost the same characteristics.

2. Ethylene Propylene Diene Monomer (EPDM)

EPDM is a class of synthetic rubber produced by copolymerizing ethylene, diene and propylene. Its properties are similar to those of natural rubber in many respects and it has been proposed as a potential substitute in tires. Beside of its elastic properties, EPDM has a good resistance to electricity and it is easy to process with many different additives. (Encyclopedia of Polymers, 2009)

EPDM is prepared by dissolving gaseous ethylene, propylene and liquid diene in an organic solvent such as hexane and subjecting them to the action of Ziegler Natta catalysts. Under the action of these compounds, the double bonds in ethylene, propylene molecules and one of the double bonds in the diene molecules are opened so that one single bond can be used to link to a carbon atom of another molecule. In this way thousands of molecules can be joined together, or copolymerized, to produce very long chainlike ethylene-propylene-diene molecules. (Encyclopedia of Britannica, 2009)

In airbag module, EPDM was used as outer part of the cover and it gives leather-like surface. The major uses of EPDM are in automobile parts like seals, wire and cable insulation, weather stripping, tire sidewalls, hoses, and roofing film.

3. Guanidine nitrate

Guanidine nitrate is a salt with high energy fuel used in gas generator applications. Guanidine nitrate can be made from guanidine and nitric acid. In another way, guanidine nitrate can be made from urea and ammonium nitrate (US patent, 1985). It has the chemical formula $C(NH_2)_3NO_3$. It has a high gas output and low flame temperature.

But in fact, guanidine nitrate has several hazards. It may explode on shock, friction, or heating. When it is combusted forms toxic and corrosive fumes like nitric acid and nitrogen oxides. In addition, guanidine nitrate is strong oxidant and reacts with combustible and reducing material. Furthermore, guanidine nitrate can be irritating to eyes and skin. It also harmful if inhaled, swallowed or absorbed through the skin (Wikipedia, 2010).

4. Polyamide 6.6

Polyamide 6.6 is one of polyamide material types known as the name "nylons". Other types of nylons are Nylon 6.12, Nylon 4.6, Nylon 6, Nylon 12 etc. Each of this material has different range of properties. Nylon is characterized by amide groups (CONH). Nylon is can be used in from of film, fiber, and molding compound.

Nylon can be made by a condensation reaction between diamines and dibasic acids to produces nylon salt. The first number of the nylon refers to the number of carbon atoms in the diamine, the second number is the quantity in the acid (e.g. nylon 6.12 or nylon 6.6). (Wikipedia, 2010)

Most of nylons tends to be semi-crystalline and are generally tough materials with good thermal and chemical resistance. Nylon also can be reinforced by introducing the glass fiber in a specific proportion. Nylons can be used in high temperature environments. Heat stabilized systems allow sustained performance at temperatures up to 185°C (for reinforced one).

In this airbag module, the PA 6.6 or Nylon fibers are used in thread and fabric for the cushion. Nylon also used as electrical insulation in the initiator inside the inflator. In another way of use, Nylon is used as fishing line and carpets. Nylon films is used for food packaging, offering toughness and low gas permeability, and coupled with its temperature resistance, for boil-in-the-bag food packaging.

5. **Polyethylene (PE)**

Polyethylene is the most widely used plastic. Its primary use is within packaging, e.g., plastic shopping bag. There are two kind of polyethylene, low density polyethylene (LDPE) and high density polyethylene (HDPE). LDPE characterized by its branch version of polyethylene and it makes LDPE has lower density, lower tensile strength but higher ductility. (Wikipedia, 2010)

LDPE is prepared from gaseous ethylene (from cracking of naphtha) under high pressures (up to 350 MPa) and high temperatures (up to 350° C) and initiated with presence of peroxide. These processes produce a polymer structure with both long and short branches. As a result, LDPE form in partly crystalline, so that has high flexibility. (Encyclopedia of Britannica, 2009)

In this particular airbag module, polyethylene is mainly used as LDPE and material for the label. In another way, LDPE mainly uses are in packaging film, trash and grocery bags, agricultural mulch, wire and cable insulation, squeeze bottles, toys, and house wares. While HDPE is used in products and packaging such as milk jugs, detergent bottles, margarine tubs, garbage containers and water pipes.

6. **Polyethylene Terephthalate (PET)**

PET is a strong, stiff synthetic fiber and resin, and a member of the polyester family polymer. PET can be spun into fibers for permanent-press fabrics, blow-molded into disposable beverage bottles, and extruded into photographic film and magnetic recording tape.

PET is produced by polymerization of ethylene glycol and terephthalic acid. When heated together under the influence of chemical catalysts, ethylene glycol and terephthalic acid to produce PET in the form of a molten, viscous mass that can be spun directly to fibers or solidified for later processing as a plastic. (Encyclopedia of Britannica)

The presence of a large aromatic ring in the PET repeating units gives the polymer notable stiffness and strength, especially when the polymer chains are aligned with one another in an orderly arrangement by drawing (stretching). The stiffness of PET fibers makes them highly resistant to deformation, so they impart excellent resistance to wrinkling in fabrics. They are often used in durable-press blends with other fibers such as rayon, wool, and cotton.

In airbag module, PET is used as material for the shunt ring inside the inflator. PET is also made into fiber filling for insulated clothing and for furniture and pillows. When made in very fine filaments, it is used in artificial silk, and in large-diameter filaments it is used in carpets. Among the industrial applications of PET are automobile tire yarns, conveyor belts and drive belts, reinforcement for fire and garden hoses, seat belts (an application in which it has largely replaced nylon), nonwoven fabrics for stabilizing drainage ditches, culverts, and railroad beds, and nonwovens for use as diaper top sheets and disposable medical garments. PET is the most important of the man-made fibers in weight produced and in value.

PET is the most widely recycled plastic. When collected in a suitably pure state, PET can be recycled into its original uses, and methods have been devised for breaking the polymer down into its chemical precursors for re-synthesizing into PET. The recycling code number for PET is #1.

7. Poly(methyl methacrylate) (PMMA)

PMMA is a synthetic resin produced from the polymerization of methyl methacrylate. PMMA has almost perfect transmission of visible light, and, because it retains these properties over years of exposure to UV radiation and weather, it is an ideal substitute for glass, shatterproof windows, skylights, illuminated signs, and aircraft canopies. PMMA is sold under the trademarks Plexiglas, Lucite, and Perspex.

PMMA is obtained principally from propylene, a compound refined from the lighter fractions of crude oil. Propylene and benzene are reacted together to form cumene, or isopropylbenzene; the cumene is oxidized to cumene hydroperoxide, which is treated with acid to form acetone; the acetone is in turn converted in a three-step process to methyl methacrylate, a flammable liquid. Methyl methacrylate, in bulk liquid form or suspended as fine droplets in water, is polymerized (its molecules linked together in large numbers) under the influence of free-radical initiators to form solid PMMA. (Encyclopedia of Britannica, 2009)

In airbag module, PMMA was used as material for the emblem. A most successful application is in internally lighted signs for advertising and directions. PMMA is also employed in domed skylights, swimming pool enclosures, aircraft canopies, instrument panels, and luminous ceilings. Because PMMA displays the unusual property of keeping a beam of light reflected within its surfaces, it is frequently made into optical fibers for telecommunication. (Encyclopedia of Britannica, 2009)

A.5. Life cycle inventory data (selected parameters)

A.5.1 Label

	Raw Material Extraction	Component Manufacturing	Transport	Total	Unit
Inflows					
Aluminium	2.000E-07			**2.000E-07**	g
Bauxite	7.625E-04			**7.625E-04**	g
Brown coal					MJ
Coal	1.607E-03			**1.607E-03**	MJ
Copper ore	2.779E-04	1.291E-07		**2.780E-04**	g
Cr in ore	2.000E-07			**2.000E-07**	g
Crude oil	3.770E-02		2.254E-04	**3.793E-02**	MJ
Electricity	2.786E-03	9.593E-05		**2.882E-03**	MJ
Fe					g
Hard coal, feedstock	2.104E-03			**2.104E-03**	MJ
Iron-ore	4.301E-03			**4.301E-03**	g
LPG					MJ
Natural gas	4.003E-02			**4.003E-02**	MJ
Peat	4.838E-05			**4.838E-05**	MJ
Uranium (as pure U)	7.482E-02			**7.482E-02**	MJ
Outflows					
Acid as H+	5.040E-05			**5.040E-05**	g
Aldehydes	6.400E-06			**6.400E-06**	g
As	2.000E-07			**2.000E-07**	g
Benzo(a)pyrene					g
BOD, fossil	1.040E-04			**1.040E-04**	g
BOD5, fossil					g
Cd		4.415E-11		**4.415E-11**	g
CH, assumed as HC	6.916E-03	1.463E-06	2.622E-05	**6.944E-03**	g
CH4	6.939E-03	3.189E-06		**6.942E-03**	g
CN-	2.000E-07			**2.000E-07**	g
CO	2.598E-03	8.152E-07	2.744E-05	**2.626E-03**	g
CO2	2.313E+00	1.266E-03	2.927E-02	**2.343E+00**	g
COD, fossil	3.559E-03	1.986E-08		**3.559E-03**	g
Cr					g
Cr3+					g
Cu	2.000E-07			**2.000E-07**	g
Dioxin					g
Fe	2.000E-07			**2.000E-07**	g
H2S	8.000E-07			**8.000E-07**	g
HCl	5.491E-05			**5.491E-05**	g
HF	2.400E-06			**2.400E-06**	g
Hg	4.000E-07	7.700E-11		**4.001E-07**	g
HNO3					g
Mn					g
Mo					g

N2O	2.000E-07	5.118E-08		**2.512E-07**	g
NH3	2.000E-07	5.917E-09		**2.059E-07**	g
NH4+	6.400E-06			**6.400E-06**	g
Ni	2.000E-07			**2.000E-07**	g
Nitrates					g
Nitrogen					g
NO2-					g
NO3-	4.000E-06			**4.000E-06**	g
NOx	1.248E-02	2.561E-06	2.561E-04	**1.274E-02**	g
Oil	1.440E-04	1.583E-07		**1.442E-04**	g
PAH	2.000E-07	4.771E-11		**2.000E-07**	g
Pb	4.000E-07	5.363E-10		**4.005E-07**	g
Phenol	2.400E-06			**2.400E-06**	g
Phospate	2.526E-05			**2.526E-05**	g
PO43-	4.320E-06	4.115E-08		**4.361E-06**	g
Propene					g
Sn					g
SO2	6.640E-03	8.098E-06	6.098E-06	**6.654E-03**	g
SOx	3.891E-03			**3.891E-03**	g
TOC	1.566E-03			**1.566E-03**	g
Toluene					g
Tot-N	5.389E-06	8.350E-08		**5.473E-06**	g
Tot-P					g
V					g
Zn	2.000E-07			**2.000E-07**	g

A.5.2 Nut

(Functional unit: 4 nuts)

	Raw Material Extraction	Component Manufacturing	Transport	Total	Unit
Inflows					
Aluminium					g
Bauxite					g
Brown coal					MJ
Coal					MJ
Copper ore		8.505E-05		**8.505E-05**	g
Cr in ore					g
Crude oil	3.079E-01		2.193E-02	**3.299E-01**	MJ
Electricity		2.212E-02		**2.212E-02**	MJ
Fe	2.236E+00			**2.236E+00**	g
Hard coal, feedstock	4.947E-02			**4.947E-02**	MJ
Iron-ore	2.236E+00			**2.236E+00**	g
LPG					MJ
Natural gas	1.192E-02			**1.192E-02**	MJ
Peat					MJ
Uranium (as pure U)					MJ
Outflows					
Acid as H+					g
Aldehydes					g
As					g
Benzo(a)pyrene					g
BOD, fossil					g
BOD5, fossil					g
Cd	4.406E-07	4.211E-08		**4.827E-07**	g
CH, assumed as HC	1.001E-03	1.414E-03	1.608E-03	**4.023E-03**	g
CH4	4.050E-03	1.365E-02		**1.770E-02**	g
CN-					g
CO	8.471E-02	1.142E-03	7.733E-04	**8.662E-02**	g
CO2	7.013E+00	4.577E+00	1.279E+00	**1.287E+01**	g
COD, fossil	4.218E-05	2.517E-05		**6.735E-05**	g
Cr	7.359E-06			**7.359E-06**	g
Cr3+					g
Cu					g
Dioxin					g
Fe	4.586E-04			**4.586E-04**	g
H2S	2.481E-07			**2.481E-07**	g
HCl	2.428E-07			**2.428E-07**	g
HF					g
Hg	7.985E-07	3.796E-07		**1.178E-06**	g
HNO3					g
Mn					g
Mo					g

N2O	2.851E-04	3.725E-05		**3.224E-04**	g
NH3	4.506E-04	1.798E-05		**4.686E-04**	g
NH4+					g
Ni	3.657E-10			**3.657E-10**	g
Nitrates					g
Nitrogen	1.468E-04			**1.468E-04**	g
NO2-					g
NO3-					g
NOx	8.556E-03	7.698E-03	3.314E-02	**4.939E-02**	g
Oil		1.303E-04		**1.303E-04**	g
PAH		1.459E-07		**1.459E-07**	g
Pb	1.668E-05	9.544E-07		**1.764E-05**	g
Phenol					g
Phosphate	1.102E-04			**1.102E-04**	g
PO43-	1.102E-04	2.075E-04		**3.177E-04**	g
Propene					g
Sn					g
SO2	1.481E-02	1.552E-02	1.956E-02	**4.989E-02**	g
SOx					g
TOC					g
Toluene					g
Tot-N	1.468E-04	2.432E-05		**1.711E-04**	g
Tot-P					g
V					g
Zn	1.127E-04			**1.127E-04**	g

A.5.3 Cushion

	Raw Material Extraction	Component Manufacturing	Transport	Total	Unit
Inflows					
Aluminium	8.874E-07			**8.874E-07**	g
Bauxite	1.200E-02			**1.200E-02**	g
Brown coal	1.948E+00			**1.948E+00**	MJ
Coal	2.668E-06			**2.668E-06**	MJ
Copper ore	6.890E-03	3.744E-03		**1.063E-02**	g
Cr in ore	6.569E-04			**6.569E-04**	g
Crude oil	3.035E+01	2.653E-01	1.452E+00	**3.207E+01**	MJ
Electricity	1.213E+00	7.032E-01		**1.916E+00**	MJ
Fe	1.253E+00			**1.253E+00**	g
Hard coal, feedstock	3.150E+00			**3.150E+00**	MJ
Iron-ore	4.775E-03			**4.775E-03**	g
LPG					MJ
Natural gas	2.020E+01			**2.020E+01**	MJ
Peat	3.225E-02			**3.225E-02**	MJ
Uranium (as pure U)	7.058E+00			**7.058E+00**	MJ
Outflows					
Acid as H+	7.706E-05			**7.706E-05**	g
Aldehydes	7.436E-06			**7.436E-06**	g
As	3.105E-04			**3.105E-04**	g
Benzo(a)pyrene	4.127E-07			**4.127E-07**	g
BOD, fossil	2.770E-03			**2.770E-03**	g
BOD5, fossil	6.731E-05			**6.731E-05**	g
Cd	1.739E-04	1.684E-06		**1.756E-04**	g
CH, assumed as HC	9.450E-02	6.277E-02	8.271E-02	**2.400E-01**	g
CH4	6.140E+00	3.052E-01		**6.445E+00**	g
CN-	2.966E-04			**2.966E-04**	g
CO	1.140E+00	3.471E-02	7.737E-02	**1.252E+00**	g
CO2	3.152E+03	1.202E+02	8.682E+01	**3.359E+03**	g
COD, fossil	4.315E+00	8.702E-04		**4.316E+00**	g
Cr	7.254E-04			**7.254E-04**	g
Cr3+	2.510E-05			**2.510E-05**	g
Cu	8.017E-04			**8.017E-04**	g
Dioxin	8.574E-11			**8.574E-11**	g
Fe	3.573E-01			**3.573E-01**	g
H2S	1.843E-02			**1.843E-02**	g
HCl	8.977E-02			**8.977E-02**	g
HF	7.155E-03			**7.155E-03**	g
Hg	2.729E-05	7.192E-06		**3.449E-05**	g
HNO3					g
Mn	1.356E-03			**1.356E-03**	g
Mo	2.622E-04			**2.622E-04**	g
N2O	8.297E-01	1.066E-03		**8.308E-01**	g

NH3	2.607E-01	3.507E-04		**2.610E-01**	g
NH4+	1.411E-04			**1.411E-04**	g
Ni	1.035E-03			**1.035E-03**	g
Nitrates	1.476E-01			**1.476E-01**	g
Nitrogen	2.510E+00			**2.510E+00**	g
NO2-					g
NO3-	1.245E-03			**1.245E-03**	g
NOx	7.216E+00	2.082E-01	1.026E+00	**8.450E+00**	g
Oil	8.662E-05	6.323E-03		**6.409E-03**	g
PAH	4.440E-04	5.046E-06		**4.490E-04**	g
Pb	5.789E-04	2.631E-05		**6.053E-04**	g
Phenol	3.697E-03			**3.697E-03**	g
Phospate	3.604E-02			**3.604E-02**	g
PO43-	2.387E-06	3.983E-03		**3.986E-03**	g
Propene	2.081E-04			**2.081E-04**	g
Sn	6.853E-05			**6.853E-05**	g
SO2	6.970E+00	4.171E-01	2.538E-01	**7.641E+00**	g
SOx	4.539E-03			**4.539E-03**	g
TOC	2.229E-02			**2.229E-02**	g
Toluene	2.010E-03			**2.010E-03**	g
Tot-N	9.303E-05	7.662E-04		**8.593E-04**	g
Tot-P					g
V	1.539E-03			**1.539E-03**	g
Zn	3.989E-03			**3.989E-03**	g

A.5.4 Can

	Raw Material Extraction	Component Manufacturing	Transport	Total	Unit
Inflows					
Aluminium		3.652E-03		3.652E-03	g
Bauxite	2.577E-02			2.577E-02	g
Brown coal	5.488E-03			5.488E-03	MJ
Coal	2.093E-02			2.093E-02	MJ
Copper ore		1.194E-03		1.194E-03	g
Cr in ore	1.541E-02			1.541E-02	g
Crude oil	4.762E-02		8.531E+00	8.578E+00	MJ
Electricity		8.873E-01		8.873E-01	MJ
Fe	7.195E+00			7.195E+00	g
Hard coal, feedstock					MJ
Iron-ore					g
LPG		5.413E-03		5.413E-03	MJ
Natural gas	1.051E-01			1.051E-01	MJ
Peat	1.563E-06			1.563E-06	MJ
Uranium (as pure U)	1.366E+01			1.366E+01	MJ
Outflows					
Acid as H+	1.224E-02			1.224E-02	g
Aldehydes	6.676E-06			6.676E-06	g
As	4.495E-05			4.495E-05	g
Benzo(a)pyrene	5.564E-09			5.564E-09	g
BOD, fossil	2.137E-05			2.137E-05	g
BOD5, fossil					g
Cd	1.893E-05	4.083E-07		1.934E-05	g
CH, assumed as HC	7.617E-03	1.353E-02	1.486E-02	3.601E-02	g
CH4	1.776E-02	2.949E-02		4.725E-02	g
CN-	1.878E-07			1.878E-07	g
CO	2.270E+00	7.540E-03	1.355E-02	2.291E+00	g
CO2	7.110E+02	1.203E+01	1.535E+01	7.384E+02	g
COD, fossil	9.282E-02	1.837E-04		9.301E-02	g
Cr	2.339E-02			2.339E-02	g
Cr3+	6.307E-08			6.307E-08	g
Cu	2.098E-04			2.098E-04	g
Dioxin	4.696E-10			4.696E-10	g
Fe	2.914E-02			2.914E-02	g
H2S	8.558E-04			8.558E-04	g
HCl	9.931E-04			9.931E-04	g
HF	4.958E-05			4.958E-05	g
Hg	3.019E-06	7.122E-07		3.731E-06	g
HNO3					g
Mn	6.071E-04			6.071E-04	g
Mo	1.601E-03			1.601E-03	g

N2O	1.052E-03	4.734E-04		1.526E-03	g
NH3	1.393E-02	5.472E-05		1.399E-02	g
NH4+	3.995E-06			3.995E-06	g
Ni	6.706E-03			6.706E-03	g
Nitrates	4.091E-02			4.091E-02	g
Nitrogen	2.499E-02			2.499E-02	g
NO2-	1.524E+00			1.524E+00	g
NO3-					g
NOx	4.813E-02	2.411E-02	2.147E-01	2.869E-01	g
Oil		1.469E-03		1.469E-03	g
PAH	1.342E-06	4.413E-07		1.783E-06	g
Pb	2.629E-04	4.960E-06		2.678E-04	g
Phenol	4.402E-07			4.402E-07	g
Phosphate	9.613E-04			9.613E-04	g
PO43-		3.806E-04		3.806E-04	g
Propene	1.031E-06			1.031E-06	g
Sn	3.288E-05			3.288E-05	g
SO2	2.568E+00	7.490E-02	7.635E-02	2.719E+00	g
SOx	3.401E-12			3.401E-12	g
TOC	1.568E-05			1.568E-05	g
Toluene	5.363E-06			5.363E-06	g
Tot-N		7.723E-04		7.723E-04	g
Tot-P		6.444E-07		6.444E-07	g
V	3.490E-06			3.490E-06	g
Zn	9.968E-04			9.968E-04	g

A.5.5 Cover

	Raw Material Extraction	Component Manufacturing	Transport	Total	Unit
Inflows					
Aluminium		8.421E-01		8.421E-01	g
Bauxite	5.546E-01			5.546E-01	g
Brown coal	1.944E-03			1.944E-03	MJ
Coal	6.366E-01			6.366E-01	MJ
Copper ore	3.421E-06	2.160E-03		2.164E-03	g
Cr	1.738E-05			1.738E-05	g
Crude oil	4.483E+00		2.032E-01	4.686E+00	MJ
Electricity	5.859E-01	5.262E-01		1.112E+00	MJ
Fe	1.753E-05			1.753E-05	g
Hard coal, feedstock	2.579E-01			2.579E-01	MJ
Iron-ore	5.710E-02			5.710E-02	g
LPG					MJ
Natural gas	3.126E+00			3.126E+00	MJ
Peat	3.097E-05			3.097E-05	MJ
Uranium	1.623E-01			1.623E-01	MJ
Outflows					
Acid as H+	2.999E-03			2.999E-03	g
Aldehydes	2.667E-05			2.667E-05	g
As	1.621E-05			1.621E-05	g
Benzo(a)pyrene	2.607E-07			2.607E-07	g
BOD, fossil	2.133E-03			2.133E-03	g
BOD5, fossil	1.611E-05			1.611E-05	g
Cd	6.851E-08	1.643E-06		1.711E-06	g
CH, assumed as HC	2.632E-01	1.428E-02	1.097E-02	2.884E-01	g
CH4	1.043E+00	1.801E-01		1.223E+00	g
CN-	5.775E-04			5.775E-04	g
CO	3.355E-01	2.049E-02	1.148E-02	3.675E-01	g
CO2	4.656E+02	1.060E+02	1.224E+01	5.839E+02	g
COD, fossil	2.415E+00	2.872E-04		2.416E+00	g
Cr	3.803E-07			3.803E-07	g
Cr3+	4.302E-08			4.302E-08	g
Cu	1.629E-05			1.629E-05	g
Dioxin	3.266E-10			3.266E-10	g
Fe	1.644E-05			1.644E-05	g
H2S	7.646E-05			7.646E-05	g
HCl	4.578E-03			4.578E-03	g
HF	2.621E-04			2.621E-04	g
Hg	3.217E-05	7.616E-06		3.979E-05	g
HNO3					g
Mn	7.030E-05			7.030E-05	g
Mo	3.747E-07			3.747E-07	g
N2O	5.736E-03	7.470E-04		6.483E-03	g
NH3	1.672E-04	4.799E-04		6.472E-04	g
NH4+	2.185E-02			2.185E-02	g
Ni	3.763E-05			3.763E-05	g

Nitrates	3.061E-05			3.061E-05	g
Nitrogen	2.962E-04			2.962E-04	g
NO2-					g
NO3-	4.555E-03			4.555E-03	g
NOx	1.161E+00	1.688E-01	1.071E-01	1.437E+00	g
Oil	5.969E-03	1.070E-03		7.039E-03	g
PAH	1.945E-05	2.237E-06		2.169E-05	g
Pb	3.268E-05	1.537E-05		4.804E-05	g
Phenol	3.860E-04			3.860E-04	g
Phosphate	1.430E-05			1.430E-05	g
PO43-	1.027E-02	2.772E-03		1.304E-02	g
Propene	2.486E-07			2.486E-07	g
Sn	1.125E-07			1.125E-07	g
SO2	1.297E+00	6.647E-01	2.553E-03	1.964E+00	g
SOx					g
TOC	2.150E-05			2.150E-05	g
Toluene	1.411E-06			1.411E-06	g
Tot-N	1.096E-02	4.114E-04		1.137E-02	g
Tot-P					g
V	1.531E-06			1.531E-06	g
Zn	1.690E-05			1.690E-05	g

A.5.6. Inflator

	Raw Material Extraction	Component Manufacturing	Transport	Total	Unit
inflows					
Aluminium		1.725E-04		1.725E-04	g
Bauxite	1.515E-04			1.515E-04	g
Brown coal	5.100E-01			5.100E-01	MJ
Coal	2.638E-01			2.638E-01	MJ
Copper ore	7.474E-04			7.474E-04	g
Cr in ore	8.861E+00			8.861E+00	g
Crude oil	3.038E+00		4.068E+00	7.106E+00	MJ
Electricity	1.956E-01	5.541E+00		5.737E+00	MJ
Fe	1.242E+02			1.242E+02	g
Hard coal, feedstock	8.719E+00			8.719E+00	MJ
Iron-ore	1.053E-02			1.053E-02	g
LPG		2.557E-04		2.557E-04	MJ
Natural gas	6.114E+00			6.114E+00	MJ
Peat	6.858E-05			6.858E-05	MJ
Uranium (as pure U)	2.523E-02			2.523E-02	MJ
Outflows					
Acid as H+	3.461E-02			3.461E-02	g
Aldehydes	2.501E-04			2.501E-04	g
As	6.209E-07			6.209E-07	g
Benzo(a)pyrene	1.285E-09			1.285E-09	g
BOD, fossil	2.286E-03			2.286E-03	g
BOD5, fossil	4.247E-04			4.247E-04	g
Cd	1.287E-05	2.771E-05		4.057E-05	g
CH, assumed as HC	8.367E-02	9.721E-01	1.679E-01	1.224E+00	g
CH4	6.813E-02	1.998E+00		2.066E+00	g
CN-	5.539E-07			5.539E-07	g
CO	5.824E+00	2.921E-01	1.474E-01	6.264E+00	g
CO2	2.115E+03	1.031E+03	1.715E+02	3.317E+03	g
COD, fossil	1.107E+00	1.126E-02		1.119E+00	g
Cr	6.591E-02			6.591E-02	g
Cr3+	8.635E-07			8.635E-07	g
Cu	7.180E-05			7.180E-05	g
Dioxin	1.290E-09			1.290E-09	g
Fe	7.635E-02			7.635E-02	g
H2S	6.877E-05			6.877E-05	g
HCl	7.918E-03			7.918E-03	g
HF	2.930E-05			2.930E-05	g
Hg	6.188E-08	4.230E-05		4.236E-05	g
HNO3					g
Mn	1.630E-03			1.630E-03	g
Mo	4.545E-03			4.545E-03	g
N2O	1.148E+00	1.285E-02		1.161E+00	g

NH3	7.662E-01	2.503E-03		7.687E-01	g
NH4+	2.104E-01			2.104E-01	g
Ni	1.904E-02			1.904E-02	g
Nitrates	1.156E-01			1.156E-01	g
Nitrogen	7.013E-02			7.013E-02	g
NO2-					g
NO3-	7.256E-02			7.256E-02	g
NOx	5.378E+00	1.873E+00	2.187E+00	9.438E+00	g
Oil	4.247E-04	1.079E-01		1.083E-01	g
PAH	8.067E-06	3.962E-05		4.769E-05	g
Pb	2.986E-04	2.825E-04		5.810E-04	g
Phenol	7.759E-06			7.759E-06	g
Phosphate	1.835E-03			1.835E-03	g
PO43-	6.722E-05	2.061E-02		2.067E-02	g
Propene	1.796E-06			1.796E-06	g
Sn	9.280E-05			9.280E-05	g
SO2	7.368E+00	5.578E+00	6.388E-01	1.359E+01	g
SOx	1.011E-02			1.011E-02	g
TOC	1.260E-02			1.260E-02	g
Toluene	5.514E-06			5.514E-06	g
Tot-N	1.455E-05	1.298E-02		1.300E-02	g
Tot-P					g
V	2.931E-06			2.931E-06	g
Zn	6.460E-04			6.460E-04	g

A.5.7 Transportation

(based on NMT 2002, as presented in Baumann & Tillman, 2004)

Type of vehicle	**Light distribution truck, short distance distribution**		**Medium sized distribution truck, regional distribution**		**Truck with semi-trailer, long distance transport**		**Truck with draw bar trailer, long distance transport**	
Pay load capacity, tonnes	1.5 - 8.5		8.5 - 15		26		40	
Energy requirement, MJ/tkm	2,41		1,87		0,72		0,65	
Emissions, g/tkm	*Euro 2*	*Euro 3*	*Euro 2*	*Euro 3*	*Euro 2*	*Euro 3*	*Euro 2*	*Euro 3*
CO2	176	176	136	136	52	52	48	48
NOx	1,6	1,1	1,2	0,9	0,46	0,33	0,42	0,3
HC	0,16	0,16	0,12	0,12	0,047	0,047	0,043	0,043
Particulate matter	0,025	0,019	0,019	0,015	0,0074	0,0057	0,0067	0,0052
CO	0,17	0,15	0,13	0,12	0,049	0,046	0,045	0,041
SO2	0,043	0,043	0,034	0,034	0,013	0,013	0,01	0,01
Euro 2: emission regulations for vehicles manufactured during 1996 - 2000.								
Euro 3: emission regulations for vehicles manufactured later than 2000.								
Type of ship	**RoRo ship**	**Small ship**	**Medium ship**	**Large ship**				
Energy requirement, MJ/tkm	0,349	0,432	0,299	0,216				
Emissions, g/tkm								
CO2	24,9	30,8	22	15,4				
NOx	0,67	0,729	0,54	0,429				
HC	0,032	0,02	0,018	0,02				
Particulate matter	0,0335	0,0246	0,02	0,0204				
CO	0,0134	0,042	0,025	0,0087				
SO2	0,424	0,515	0,36	0,262				

A.5.8 Electricity

Inventory table for electricity production systems, selected parameters
Based on Frischknecht et al. (1996).

Direction	Flow type	Substance	Unit	Environment	Hard coal	Oil	Fuel gas	Lignite	Nuclear	Biofuel	Hydro electricity	Wind
input	natural resource	copper in ore	kg	ground	4,280	4,180	4,390	5,460	2,260	0,444	0,058	41,400
		crude oil	kg	ground	2580	73100	1260	478	246	2777	75	670
		lignite	kg	ground	1950	1230	265	41400	238	126	65	234
		limestone	kg	ground	2210	431	200	1880	163	86	655	755
		natural gas	Nm3	ground	1898	6058	59112	392	415	285	24	378
		hard coal	kg	ground	183000	1490	12100	1400	1260	293	294	1530
		uranium ore	kg	ground	0,133	0,084	0,018	0,095	7,850	0,009	0,004	0,017
		water	kg	ground	10700000	19300000	608000	13500000	2530000	65800	11700	46450
		wood	kg	ground	1320,000	28,600	104,000	27,500	21,400	174000,000	2,950	15,700
output	emission	Cd	kg	air	0,002	0,016	0,000	0,009	0,000	0,000	0,000	0,001
		CH4	kg	air	1003,500	307,000	373,700	31,490	10,260	13,690	2,390	15,280
		CO	kg	air	56,600	75,150	81,970	45,100	6,010	187,890	5,790	34,610
		CO2	kg	air	275833	229380	245831	370979	3605	8964	1045	46
		Cs-134	kBq	air	0,039	0,025	0,005	0,028	2,300	0,003	0,001	0,005
		Hg	kg	air	0,033	0,001	0,001	0,019	0,000	0,013	0,000	0,000
		Kr-85	kBq	air	5030000	3180000	693000	3590000	297000000	328000	170000	630000
		N2O	kg	air	1,790	5,530	1,500	1,800	0,800	13,600	0,015	0,076
		NH3	kg	air	1,497	0,224	0,060	1,800	0,051	0,003	0,006	0,021
		NMVOC	kg	air	33,900	588,000	62,000	12,600	3,930	45,800	0,947	10,540
		NOX	kg	air	451,700	504,600	408,440	558,000	9,599	252,000	3,196	9,845
		PAH	kg	air	0,004	0,005	0,022	0,004	0,000	0,000	0,000	0,001
		PM	kg	air	321,590	96,870	16,130	257,660	7,080	29,400	2,090	12,160
		Pb	kg	air	0,066	0,136	0,004	0,029	0,002	0,009	0,001	0,027
		Rn-222	kBq	air	7300000	4620000	1010000	5210000	432000000	478000	0	905000
		SO2	kg	air	1062,700	2359,400	58,290	3623,530	25,100	42,700	2,860	19,040
		Sr-90	kBq	air	0,054	0,034	0,007	0,038	3,170	0,003	0,002	0,007
		U-238	kBq	air	12,184	0,317	0,078	5,024	22,776	0,337	0,018	0,069

		COD	kg	water	1,180	6,140	0,800	0,098	0,090	0,554	0,026	0,305
		Cs-134	kBq	water	6,888	4,359	0,900	4,915	407,620	0,450	0,233	0,865
		N total	kg	water	0,714	7,423	0,270	0,098	1,491	0,603	0,019	0,150
		Oil	kg	water	2,550	69,800	2,960	0,474	0,252	10,000	0,075	0,685
		PO4-3	kg	water	17,500	0,193	1,190	0,138	0,128	0,056	0,029	0,149
		Sr-90	kBq	water	6,490	4,100	0,894	4,630	384,000	0,424	0,220	9,815
		U-238	kBq	water	25,700	1,820	0,281	1,450	109,000	0,133	0,069	0,256
		Electricity	**TJ**	**technosphere**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	emission	highly radioactive waste	M3	technosphere	0,000	0,000	0,000	0,000	0,001	0,000	0,000	0,000
		medium & low radioactive waste	M3	technosphere	0,000	0,000	0,000	0,000	0,016	0,000	0,000	0,000
		waste in deposit	kg	technosphere	65800	2000	5020	48300	1520	3840	5670	987

Electricity production based on different energy sources (in %), in different countries

	Country	Year	Hard coal	Oil	Natural gas	Lignite	Nuclear	Hydro electricity	Wind	Other
1)	France	1998	7,01	2,30	0,98	0,35	76,54	12,24	0,01	0,58
1)	Germany	1998	28,99	1,15	9,83	25,24	29,26	3,12	0,83	1,58
1)	Italy	1998	10,84	42,31	27,95	0,13	0,00	16,25	0,09	2,43
1)	Sweden	1998	1,99	2,06	0,27	0,04	46,50	46,98	0,20	1,95
1)	United Kingdom	1998	34,50	1,60	32,52	0,00	28,08	1,47	0,25	1,58
1)	United States	1998	50,72	3,87	14,66	2,02	18,77	7,71	0,08	2,15
2)	Romania	2006	0,00	2,56	18,87	40,30	8,98	29,28	0,00	0,01
3)	Czech Republic	2006	0,00	0,31	3,90	59,90	30,87	3,86	0,06	1,10
4)	Mexico	2006	12,71	21,57	45,51	0,00	4,35	12,17	0,02	3,67

1) Data is available for 2006 from IEA website, but "Hard coal" and "Lignite" are grouped under "Coal". For better accuracy, it was decided to use the 1998 numbers instead.
2) Romania: Coal for electricity generation is mostly lignite (23713 kton) with a little sub-bituminous coal (42 kton).
3) Czech Republic: Coal for electricity generation is mostly lignite (26978 kton) with a little sub-bituminous coal (1160 kton).
4) Mexico: Coal for electricity generation is sub-bituminous coal (14697 kton).