CHALMERS

Environmental Evaluation of Bio-Composites Using LCA

Master's Thesis within the Industrial Ecology programme

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Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2013

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Cover:
Photograph of forest thinning by Jonas Hermansson

Insert:
DuraPulp sheet, black, 150 g/m2, for compression moulding

Chalmers Reproservice
Göteborg, Sweden

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ABSTRACT

A bio-composite is a material based on a bio-fibre and a polymer; either being bio-based or fossil based, and has been developed in order to e.g. decrease the use of limited substances, such as crude oil (used for plastic manufacturing). In order to investigate the environmental advantages and drawbacks of the bio-composites this environmental evaluation has been conducted using the life cycle assessment methodology. The goals of this study were to evaluate the main environmental impacts arising from the different phases of the bio-composites lifespan, to compare impacts deriving from the choice of polymer and to suggest methodological choices for the comparison of a short lifespan product to a long lifespan product. The results show that bio-composites with a lower input of polymer have a smaller environmental impact than bio-composites with a higher share and that a short lifespan application offsets the most impacts. Findings also show the importance of choosing a proper dimension for the reference flow when dealing with materials and use phases that depends on weight to fulfil a just evaluation of the materials.

Key words: Bio-Composite, Life Cycle Assessment, Pulp, Polymer, Renewable

Användandet av LCA för miljöbedömande av bio-kompositer
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SAMMANFATTNING

Bio-kompositer består av en bio-fiber och en polymer (vilken kan vara av både fossil och förnyelsebart ursprung). De har utvecklats för att minska användandet av begränsade resurser, såsom råolja vilket tillexempel används i framställningen av plast. Denna studie genomfördes för att undersöka vilka fördelar och nackdelar som förknippas med bio-kompositen. Målen med analysen var att undersöka vilka faktorer under kompositens livslängd som mest påverkar miljön, att undersöka de miljömässiga skillnaderna mellan valet av en fossil- eller förnyelsebar polymer samt att ge förslag för hur en produkt med en lång livslängd kan jämföras med en produkt med kort livslängd. Resultaten visar att bio-kompositer med en mindre andel polymer har en lägre miljöpåverkan än kompositer med en hög samt att en applikation med kort livslängd är mest fördelaktigt för bio-kompositen jämfört med en plastprodukt. Resultaten pekar även på vikten av att välja en lämplig dimension på referensflödet när målet är att jämföra material och användarfaser som beror på massan.

Nyckelord: Bio-Komposit, Livscykel Analys, Pappersmassa, Polymer, Förnyelsebar

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Preface

For this environmental evaluation, an LCA for the material DuraPulp and its alternative counterpart materials was conducted. The study was carried out by Frida Hermansson under the supervision of Matty Janssen between January and June 2013, as a master thesis at the division of Environmental Systems Analysis at Chalmers University of Technology in collaboration with *Södra Skogsägarna Ekonomisk Förening*.

I would like to thank the staff at Södra, especially Fredrik Gellerstedt, Eva Thuresson and Gustaf Collin for their time and help. I would also like to thank my supervisor Matty Janssen for all the help as well as for the patience he has shown me during the conduction of this project. For this I am very grateful.

Frida Hermansson
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Abbreviations

AOX	Absorbable Organic Halides
AP	Acidification Potential
Bio-PE	Bio-Polyethylene
BOD_7	Biochemical Oxygen Demand, 7 days
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
DAP	Depletion of Abiotic Resources
D:PLA,A	DuraPulp: Polylactic acid, Anaerobic digestion
D:PLA,I	DuraPulp: Polylactic acid, Incineration
D:PLAR,A	DuraPulp: Polylactic acid-Renewable energy certificates, Anaerobic digestion
D:PLAR,I	DuraPulp: Polylactic acid-Renewable energy certificates, Incineration
EP	Eutrophication Potential
FPC	Fibre Polymer Composite
GWP	Global Warming Potential
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
N_{tot}	Total Nitrogen
PLA	Polylactic acid
PM:PE	Pulp mix: bio-Polyethylene
PM:PP	Pulp mix: Polypropylene
POCP	Photochemical Ozone Creation Potential
PP	Polypropylene
PP:P	Polypropylene: 100% polymer
PS	Polystyrene
P_{tot}	Total Phosphor
REC	Renewable Energy Certificate
SS	Suspended Solids, retained on filter mesh of 70 pm
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UCTE	Union for the Co-ordination of Transmission of Electricity
WPC	Wood Polymer Composite

1. Introduction

Södra Skogsägarna Ekonomisk Förening is a Swedish forestry company based in the south of Sweden. Sawn timber and market pulp are the two largest products in the Södra product portfolio. Due to structural changes in the paper market where digital media are replacing paper in many segments, Södra is searching for other applications for the pulp where the outstanding properties of wood fibres are beneficial. Such an application is bio-composites and Södra has developed a unique concept called DuraPulp, based on pulp and polylactic acid, which is a renewable and biodegradable bio-polymer based on corn. On the market today, one of the most common bio-composites is wood polymer composite (WPC), which consists of wood flour and polypropylene (a fossil based polymer). Another type of bio-composite that presently is being developed is fibre plastic composite (FPC), which consists of pulp and polypropylene. These bio-composites are and/or will be in competition with DuraPulp, at least in the aspect of consisting of a wood based fibre. It is important to investigate the environmental impacts of the bio-composite in its different applications, arising from emissions from, for example, the use phase or the recycling process, as well as to investigate the advantages and drawbacks of using a renewable polymer in the matrix. The main advantages of using renewable bio-based matrices are 1) the decrease of dependence on non-renewable fossil-based polymers with similar qualities, 2) the minimization of non-degradable plastic waste (cannot be applied to all bio-polymers) as well as 3) the reduction of carbon dioxide emissions (Pilla, 2011). Regarding the natural fibres which the bio-composites consist of, the rewards of choosing them over a fossil-based fibre is that they are carbon dioxide neutral and that the processing environment for the employees is lenient regarding the aspects of skin and respiratory problems (John & Thomas, 2008). The fact that natural fibres are available worldwide is also a big advantage compared to the conventional ones (e.g. glass fibre). Even though bio-based polymers have many advantages, changing from fossil-based to bio-based polymers can induce additional land use and/or land use change with related environmental impacts. There are also non-environmental (i.e. social and economical) impacts connected to land use change, such as the possible increase in food prices (Weiss et al. 2012).

The world is presently facing a waste issue connected to the increased global demand for goods. Cooper (2004) describes the setback that occurs if a product would be discarded before the intended life span has expired. This would lead to an increased environmental impact, which would be contradicting with the main goal of the production of durable products (i.e. long lifespan products). He moreover writes that maximum life length is not the main goal, but optimal life length is. Finding the optimal life length depends on the question of concern. If the main concern regarding the product in question is increased waste in landfills, improved durability is most important. If the concern instead is regarding the depletion of abiotic resources, such as crude oil, it might be more appropriate to aim for a shorter lifespan (considering technology development) and exchange the older product to a new, more developed product, with a better performance in the use phase. Additionally, it is not only the collection rate (i.e. percentage of product being sent to recycling) that is determining if the recycling contributes to the environmental gains, but also the number of times the material can be recycled (i.e. if a material degrades easily but has a high collection rate compared to a low collection rate of a material that does not degrade). Today the *European Commission of End of Life for Consumer Products* only focuses on the collection rate of the product, not the number of times a material can be recycled and retains sufficient quality (Birat et al. 2006). For example, steel degrades less than paper and can thus be recycled a higher number of times, but perhaps with a lower collection rate.

2. Literature Review

Even though man has used bio-composites for a long time, the literature on which bio-composite applications are environmentally preferable available today are limited. Work currently accessible generally investigates different compositions of bio-composites, varying the polymer origin or type of bio-fibre, examining, for example, the bio-composite's physical properties. Some examples of studies performed on bio-composites are Amin et al. (2007) covering the thermal and mechanical properties of bio-composites made from oil palm empty fruit bunch fibres and kaolinite, and Li et al. (2011) describing the microstructure of a bio-composite made from acorn powder and PLA.

The bio-composite DuraPulp manufactured by the forestry company Södra consists of 70% pulp and 30% polylactic acid (PLA), a polymer based on corn starch with intended applications in the car industry (e.g. as a car door panel) or in the food industry as a high-end packaging unit. A study covering different applications of bio-composites in a general manner was conducted by Pandey et al. (2010), mainly focusing on mechanical properties, although also to some extent environmentally, of different applications of bio-composites such as in the car industry and applied in buildings, although not identifying the most beneficial application of the material.

2.1 Choice of Material

A bio-composite consists of a bio-fibre and a polymer, where the polymer can be either fossil based or bio-based. Mohanty et al. (2002) divides the fibres used in bio-composites into two groups: wood fibres and non-wood fibres. Up until now, non-wood fibres, such as hemp and kenaf (plant-based fibres), are preferred by the automotive industry. The choice of pulp (wood based fibre) in the bio-composite matrices in the application of the car door panel is therefore currently not common and requires further research and evaluation.

As for biopolymers in bio-composites, polylactic acid in bio-composites is a common choice, as polylactic acid is one of the biopolymers being manufactured at a larger scale. Another possible biopolymer for bio-composites is bio-PE, described by Liptow and Tillman (2009), which can be manufactured using sugar cane as the biomass feedstock. An alternative polymer for bio-composites is polypropylene, which usually is fossil-based. An advantage using biopolymers instead of fossil polymers in bio-composites is that some (although not all) biopolymers are biodegradable; among the polymers previously mentioned it is only PLA that is biodegradable. Biodegradable materials are materials that can be broken down to e.g. CO_2 and soil after contact with bacteria and microorganisms. This is beneficial for the food packaging application where the packaging can be sent to anaerobic digestion as an end of life treatment, instead of landfilling or incineration. The produced biogas from the anaerobic digestion process can be used as an energy source for the society, offsetting natural gas. Although, biodegradability has some drawbacks. For example, one of the challenges with biopolymers would be to keep them intact during the storage and use, and only degrade after their intended lifespan has ended and are disposed (Mohanty et al. 2002)

An example of a study comparing packaging unit made from a fossil polymer to a biopolymer using LCA is one by Bohlman (2004), where a packaging unit made of polypropylene and a packaging unit made of PLA are compared. The functional unit was set to 1000 kg of yoghurt purchased by the consumer. The system boundaries where established on the basis of when considering products derived from commercial crops, standard is to place the starting boundary from when the seed is put in the soil so that the energy use in the cultivation phase as well as the production and use of fertilizers are taken into account. The study was assumed to take place in the United States, and as most household waste in the United State is landfilled, this is chosen as the end of life treatment. Conclusions drawn are that the packaging made from PLA is more energy efficient than the one made from polypropylene, but that the green house gas emissions are equal under certain assumptions.

2.2 Materials Lifecycle and Different Applications

Lee and Xu (2005) write that since packaging affects the environment as a consequence from the manufacturing phase, distribution phase and the disposal phase, and that as soon as it gets to the consumer, it has served its purpose, it is an important application of material to consider. Furthermore, they write that lightweight materials in packaging will reduce the environmental burden of the application (i.e. connected to the transportation), but if the material used for transportation is decreased too much in terms of weight or bulkiness, it might fail in the protection of the packaged goods sufficiently. This may lead to the goods being damaged and as a result not being used, and the total environmental burden will then as a consequence increase.

Today, most of the LCA:s performed are for packaging units based on either pure plastics or paper and not on bio-composites, which therefore may be considered to be a new material for this particular application. An example of an LCA covering packaging is a study performed by De Monte et al. (2005), evaluating different packaging alternatives for coffee. The system boundary excluded the cultivation, manufacturing and transportation of the coffee (i.e. until the end of the roasting process) in order to focus of the packaging and not the coffee. The functional unit was chosen to be one kg of packed coffee, in order to enable evaluation of different types of packaging units. The results shows that choosing plastic laminated packaging over metallic cans will decrease the environmental burden, as well as to decrease the weight of the packaging and increase the energy efficiency in the manufacturing process. Another way of decreasing the environmental burden is to increase the recycling of the material. Eide (2002) performed an LCA on milk including the milk production, the packaging and the waste management. The functional unit of the study was chosen to be 1000 litres of drinking milk at the consumer. Land use, capital goods and interactions between crops in crop rotation were not taken into account. The results shows that it is the agriculture and the dairy production that contributes the most to the environmental burden for the milk, but that the transportation of the packaging consumed more energy than the combined transportation of the milk to the dairy and distribution. Another study that focuses on milk packaging was performed by Xie et al. (2011). This particular study compares two different types of packaging for milk; 1) a laminated foil made from paper-polyethylene-aluminium (i.e. a composite) and 2) pure polyethylene. The functional unit was chosen on the basis of equivalent functions, this was set to 1000 litres of milk (leading to 1000 composite packages of 1 litre each and 5000 plastic packages of 0.2 dl each). The study does not include the use phase of the milk, maintenance of mechanicals and capital goods. The results of the study show that the composite packaging has slightly higher environmental impact, arising from the use of fossil fuels, land use and respiratory inorganic categories compared to the pure plastic packaging. Another reason for the higher environmental impact for the composite is the lack of good reuse and recycling processes.

Bio-composites were implemented in the car industry in the 1930's to 1940's (Pandey et al. 2010), although environmental assessments of car door panels made out of bio-composites compared to conventional materials have not been reported widely in the literature so far. One study that essentially focuses on the environmental performance of car parts manufactured from a conventional composite and a bio-composite is performed by Alves et al. (2010). This study compares the choice of fibre in the composite; either being glass fibre or jute, and the functional unit was chosen to be the frontal bonnet of the buggy, or "the engine cover of 0.35 m^2 which achieves the required mechanical and structural performance". The system boundaries were set to include the whole life cycle of the bonnet and also the influence for the whole vehicle. The conclusions of this study were that the jute-based composite enhances the environmental performance of the car due to a lower weight and therefore less fuel use in the use phase. Luz et al. (2010) performed an environmental study comparing the environmental benefits by substituting talc by sugarcane bagasse in polypropylene composites for application in the car industry. The functional unit of the study was chosen to be area covered (of the car). The system boundaries contained the raw material extractions, agricultural activities, use phase and end of life of the vehicle as well as the transportation processes. Some of the conclusions of the study were that the growing of the sugarcane in the cultivation phase offsets global warming potential by the absorption of the carbon dioxide and that the production process is cleaner and the sugarcane composites weighs less compared to the talc.

2.3 Comparison of Lifespans

To the author's knowledge, there are no studies that focus on the comparison of the preferred application depending on lifespan of a material from an environmental point of view. A desirable outcome of comparing product lifespans using LCA would be to make a judgment on what application is preferable for the material in question (i.e. offsetting the most emissions compared), either having a long lifespan and not being recyclable or a short lifespan but with recycling possibilities. Also, methodological directives for performing an LCA in order to make these comparisons are needed, for example choosing an appropriate functional unit that allows for comparison and which data quality that is required for the two different applications.

A specific case where the recyclability of the material has been shown to be of importance is in the car door panel application. The European Union has a directive that says that in the year 2015, 85% of the cars' weight should be reused or recycled (EU 2000). This means that there is a need of increasing the recyclability and durability (longer lifespan and being able to reuse/recycle) of the materials used in the cars. There have been studies examining the car door panels´ environmental impact. An example of one of these studies is Muñoz et al. (2006) who described the LCA of a recyclable car door panel in order to meet the legislations for 2015 set by the End-of-Life Vehicles directive. Results show that the recyclable car door panel will lower the environmental impacts compared to a conventional one not being recycled.

2.4 Final Remarks

Although bio-composites have been used in various applications for a long time, the most common polymers of choice up until now have been fossil based, leading to a knowledge gap for bio-composites based on bio-polymers and their environmental properties compared to conventional polymers. Moreover, there have been many studies on bio-composites comparing mechanical properties, but not as many investigating the environmental impacts arising when choosing different polymers and fibres, as well as what factors have the greatest influence on the material during its lifetime. Still, as for this aspect, the weight of the material, affecting the transportation and sometimes the use phase, is often in the available literature considered to be an important factor as well as the manufacturing process possibility of recycling (which is connected to the choice of material). Correspondingly, the appropriate methodological choices to make when comparing a long lifespan product (i.e. a durable product) to a recyclable product is lacking in the literature today. Most packaging studies today are comparative regarding the selection of different materials, considering the methodological choices of picking the same function for the systems. When comparing a durable product to a recyclable one with a shorter lifespan, it is most likely that the intended function of the system will not be equal. This also leads to different system boundaries compared to when considering the same functional unit, proper methodological choices for making such a comparison is today missing from the body of knowledge.

3. Methodology

3.1 The LCA Procedure

Bauman and Tillman write in the Hitchhikers guide to LCA: "in an LCA study, the whole industrial system involved in the production, use and waste management of a product or service is described" (Bauman and Tillman 2004 p.19). When conducting an LCA, the practitioner (i.e. the person performing the study) follows the procedure described in figure 1.

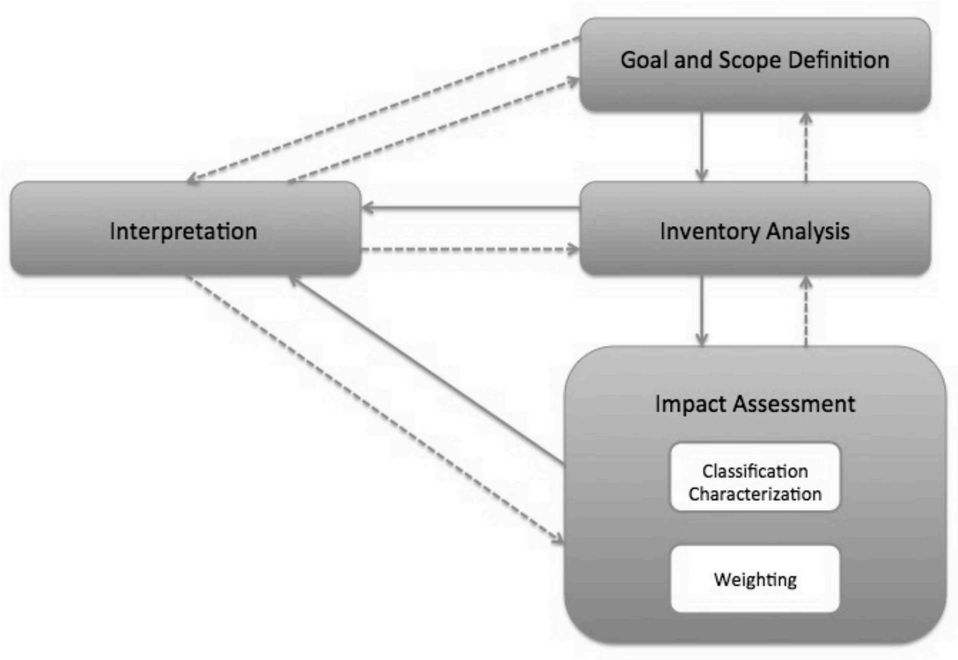

Figure 1: The LCA procedure, where the dotted lines indicate iteration possibilities (Adapted from Baumann and Tillman 2004).

3.2 Goal and Scope Definition

The first step of an LCA study is the goal and scope definition. In the goal and scope definition, the purpose of the study and the modelling aspects are chosen. The goal of the study includes the intended application and reason for carrying out the analysis, as well as the intended audience. The scope concerns the modelling aspects of the LCA, including the context of the study, the functional unit (which reflects the function of the product or service that is under study), system boundaries (e.g. timeline, technical boundaries and geographical boundaries), what types of environmental impacts that are being considered, the level of detail in the data required for the study (i.e. if the data should be average or site-specific), how to allocate the impacts between different products sharing the same processes, as well as how the project is planned (Baumann and Tillman 2004).

3.2.1 Goal Definition

This LCA study was initiated by *Södra Skogsägarna Ekonomisk Förening*. Södra is interested in bio-composites and in what ways it can change the environmental impact of the use phase of different applications when compared with conventional materials, as well as the impacts from the manufacturing phase and the end of life treatment. The applications of the material for this study were divided into a long lifespan case represented by a car door panel, and a short lifespan case, represented by a small packaging unit intended for the food industry.

The three main goals of this study were:

1. To compare a bio-composite based on a bio-based polymer (polylactic acid and bio-polyethylene) and fossil-based polymer (polypropylene) and pure plastics (i.e. virgin polypropylene and polystyrene).
2. To investigate the main factors for the environmental impacts of bio-composites.
3. To suggest methodological choices that will help stakeholders to gain insight about the trade-off of choosing between a short lifespan and an extended lifespan application of a material.

The materials being considered in this study were 1) DuraPulp, which is a bio-composite consisting of 70% pulp and 30% PLA/PLA-REC, 2) pulp mix based on 70% pulp and 30% polymer (bio-PE or PP) 3) FPC consisting of 40% pulp and 60% PP, 4) WPC consisting of 50% wood dust and 50% polymer, 5) 100% polypropylene, and 6) 100% polystyrene.

The analysis was conducted using the attributional LCA methodology. Attributional LCA is primarily used when the goal is to describe the environmental impact of a product or service. Moreover, attributional LCA is comparative and retrospective. This type of analysis is also suitable for when the producers of the LCA are not the same as the users of the LCA (Baumann and Tillman 2004), which corresponds to the conditions of this study.

3.2.2 Scope Definition

In this section, the models and choices needed to fulfil the goal of the study are defined (Baumann and Tillman 2004).

3.2.2.1 Overall Flowchart

Figure 2 shows the general flowchart for the production of bio-composites. This includes the raw material extraction, the manufacturing phase, the use phase and the end of life treatment. The pure virgin plastic cases look equivalent to figure 2, although the pulp production and the connected raw material extraction are excluded, figures exclusively for the pure plastics cases can be found in chapter 4.

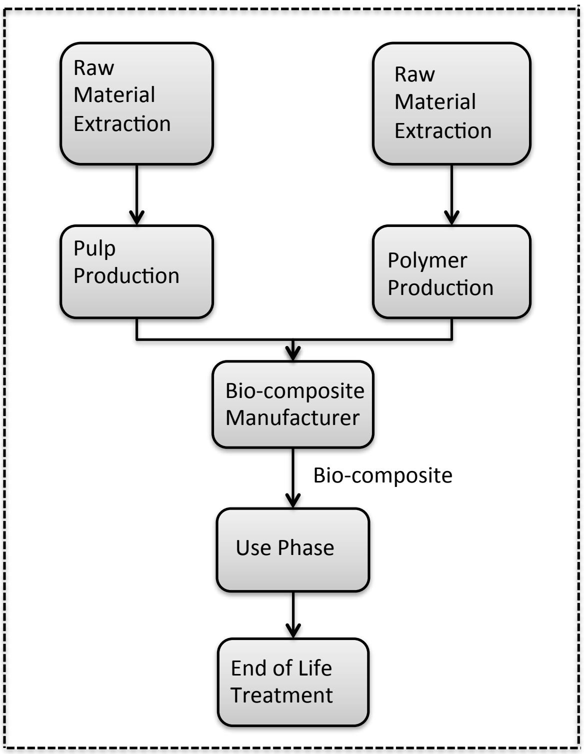

Figure 2: The initial flowchart of bio–composite life cycle, where the dotted line corresponds to the system boundaries.

3.2.2.2 Functional Unit

The functional unit is defined by the function of the product in question (Baumann and Tillman 2004). For this study, two functional units were chosen, representing one product with a long lifespan and one product with a short lifespan. For the long lifespan case, the functional unit *1 car door panel* was chosen (component protecting the electronics on the inside of the car door), and for the short lifespan case it was set to *1 packaging unit* (i.e. high end food packaging tray).

Materials considered for the car door panel:

- DuraPulp: PLA (70% pulp and 30% PLA)
- DuraPulp: PLA-REC (70% pulp and 30% PLA-REC)
- Pulp mix: bio-PE (70% pulp and 30% bio-PE)
- Pulp mix: PP (70% pulp and 30% PP)
- Pure Virgin Polypropylene (100% PP)
- Wood flour Plastic Composite (40% pulp and 60% PP)
- Fibre Plastic Composite (50% pulp and 50% PP)

The densities for the different materials used for manufacturing the car door panel can be found in Appendix A, table A1

Materials considered for the packaging unit:

- DuraPulp: PLA (70% pulp and 30% PLA)
- DuraPulp: PLA-REC (70% pulp and 30% PLA-REC)
- Pulp mix: bio-PE (70% pulp and 30% bio-PE)
- Pulp mix: PP (70% pulp and 30% PP)
- Pure Virgin Polypropylene (100% PP)
- Pure Virgin Expandable Polystyrene (100% EPS)

The densities for the different materials used for manufacturing the packaging unit can be found in Appendix A, table A5

The reference flows in this study were determined to be the output of 1dm^3 material from the manufacturing process of the car door panel (corresponding to the assumed measurements for the car door panel of 1m*0.5m*0.002m) and 0.026 dm^3 material for the packaging unit, corresponding to the normal volume of a packaging unit manufactured from DuraPulp: PLA (See Appendix A for details and calculations).

3.2.2.3 Choice of Impact Categories and Method of Impact Assessment

According to the ISO standards the following impact categories should be taken into account when performing an LCA: *resource use*, *human health* and *ecological consequences*. In order to increase the understanding of these so-called damage (or endpoint) categories, they are partitioned into different midpoint impact categories. These include the categories *depletion of abiotic resources* (use of fossils), *climate change* (characterized by how much the green house gases increase the radiative forcing in the atmosphere), *photochemical ozone creation potential* (photo-oxidants are formed from NO_x and hydrocarbons in the presence of sunlight), *acidification* (a consequence from the acidic ion H^+) and *eutrophication* (i.e. humans emit excess nutrition into the environment) (Baumann and Tillman 2004).

Resource use, which includes the depletion of abiotic resources and impact of land use competition is an issue that globally has been recognised, and that is strongly connected to the industry due to energy use and in the case of composites due to fossil based polymers use. Moreover, since this is a study concerning bio-composites, which are based on biotic resources (i.e. renewables), it is important to investigate if these really are an alternative for fossil polymers. Impact of land use competition is not included in this study due to a lacking methodology.

The choice of impact categories describing ecological consequences derives from the fundamental environmental issues that are a consequence of human activities. These include, as already mentioned; climate change eutrophication, acidification and photochemical ozone creation potential. These impact categories were chosen due to the fact that they are of great importance and relevance for the applications of the bio-composites in this study. Climate change is strongly connected to the manufacturing and the fuel use, eutrophication to the fertilization of the biopolymers raw material and acidification and photochemical ozone creation potential to the gasoline combustion and electricity production (used in manufacturing). Moreover the characterizations of these are fairly certain compared to, for example, the land use category where more research is needed. The different impact categories will be presented in the form of graphs and tables, and a discussion and analysis of what the sources of the main environmental impacts are will be included.

3.2.2.4 System Boundaries

Regarding geographical system boundaries, the manufacturing phase, use phase (excluded for the packaging unit due to the fact that the use phase is allocated to the material being packaged) and end of life treatment of the bio-composite are restricted to take place in Sweden. The extraction of polymer raw material, such as oil and natural gas for polypropylene or corn for PLA, which occurs outside of Sweden, is included. The trees used for manufacturing pulp and wood flour are assumed to come from Sweden.

As for technical system boundaries, cut offs include the impact from the employees, the real estates (both the construction and maintenance) and the impacts from the manufacturing and maintenance of the included process units.

The timespan for the car door panel was set to 17 years, which corresponds to the average life expectancy of a car (Jernkontoret 2003). On the one hand, it can be assumed that the door panel does not have any effect on the lifespan of the car; on the other hand, the door panel will be dependent on the car life span. The lifetime for the packaging unit was chosen to be 1 month, based on the assumption that it contains a product with high turnover ratio and that the packaging will be discarded shortly after being purchased, e.g. a food container. The mass of the reference flow will be normalized to the same timespan in order to portray the lower raw material extraction and manufacturing rate of a long lifespan product and the higher rates for a short lifespan product.

3.2.2.5 Data Quality Requirements

In order to guarantee a high data quality, the aspects of relevance, reliability and accessibility must be considered. The relevance factor corresponds to how the data matches the question and study in terms of geographical terms, technical terms and according to time. The reliability depends on the consistency and precision of the data. The final factor, accessibility also refers to consistence, but also reproducibility of the data (Baumann and Tillman 2004).

Data sources mainly used for this study:

- Literature/scientific articles (i.e. peer reviewed journals; e.g. Journal of Clean Production)
- Databases (i.e. the ecoinvent database)
- Manufacturers (e.g. Södra, Natureworks)

This study has primarily used data collected from the manufacturers; when data has been lacking therefrom, the ecoinvent database has been used. Since it is an accounting LCA, average data have been used in the inventory.

3.2.2.6 Assumptions and Limitations

Assumptions in this study:

- All of the bio-fibres in this study are assumed to come from Swedish wood in the vicinity of *Södra Cell Värö*, which is where the pulp is manufactured.
- The pulp manufacturing process was assumed to be the same for all types of bio-composite considered (based on either renewable or non-renewable polymers).
- For the DuraPulp and pulp mix manufacturing processes, the fibre to polymer ratio was assumed to be 30% polymer to 70% pulp, and after recycling; the fibre to polymer ratio was assumed to change to 40% pulp to 60% polymer, and is only changed first time of recycling. The polymer added in the recycling process is assumed to be the same as in the original matrix.
- The inputs needed when manufacturing the DuraPulp and pulp mixes (i.e. mixing pulp and polymer) was assumed to be negligible
- For the virgin polystyrene case, the density was assumed to be the same as for DuraPulp: PLA. Moreover, no recycling is assumed due to the lack of proper recycling schemes for expanded polystyrene (Tan and Khoo 2005), since the functional unit is one unit of small packaging, it is assumed that there is no reuse and that the material goes to incineration. The data for the polystyrene manufacturing process is for expandable polystyrene and foaming (ecoinvent n.d.)
- The mouldings of the materials were assumed to be compression moulding for DuraPulp and pulp mix cases and injection moulding for the pure virgin polymer cases as well as for WPC and FPC.
- The car door panel is assumed to have the measurements 1m*0.5m*0.002m.
- The packaging unit made from DuraPulp: PLA is assumed to weight 20 grams and the related volume is assumed for all materials.
- The transportation of the packaging unit is excluded due to the fact that it is assigned to the packaged goods and not the packaging itself.
- The car door panel is assumed to be incinerated after use.

Limitations in this study:

- Incomplete methodologies, for example in the case of impacts of land use and land use change, and biodiversity, where the incomplete set of data and limited knowledge on how land use change can have effects on the environment in different parts of the world (Baumann and Tillman 2004).
- Lack of data, for example concerning incineration of PLA and pulp, where plastic mixture and packaging cardboard are to be assumed to be equivalent. Also, a lack of available data for certain chemicals has led to a cut-off in the modelled manufacturing processes.

3.2.2.7 Allocation

Allocation is done when several products or services share the same processes and if the load of the environmental impact is expressed in relation to one of these products or services. Usually, there are three main situations where allocation is needed; multi-output processes, multi-input processes (e.g. waste treatment) and open loop recycling. (Bauman and Tillman 2004). In this study, allocation is done due to recycling of the packaging unit and follows the ISO 14049 (ISO 14049 2000) guidelines, which takes into account collection rate and the number of uses for the material as a consequence of the collection rate. Calculations can be found in Appendix A.

4. Life Cycle Inventory

The life cycle inventory (LCI) is a combination of site-specific data (Södra pulp manufacturing process) and average data collected from the ecoinvent database (e.g. polymer manufacturing) as well as literature and environmental reports. In this section, the simplified flowcharts for the different processes can be found (figures 3 to 6). For more detailed flowcharts for the different processes, please see Appendix B and C. More specific process details can be found further on in this chapter.

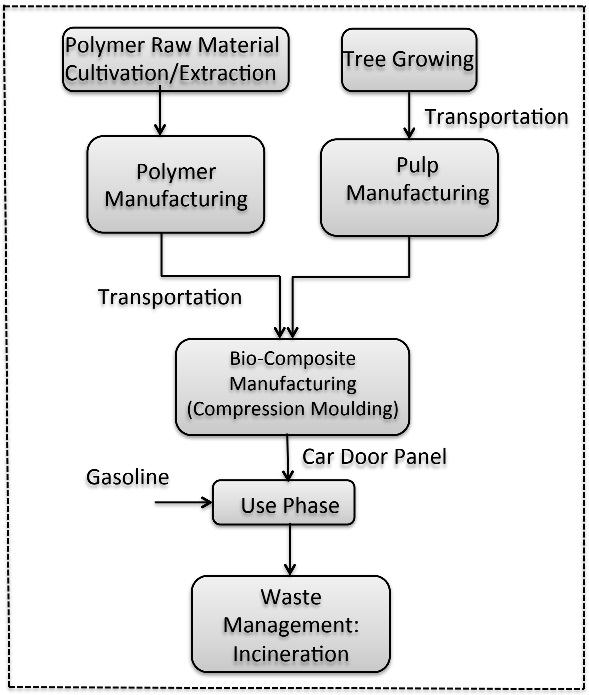

Figure 3: General simplified flowchart for the bio-composite (DuraPulp, pulp mixes, WPC and FPC) based car door panels' lifecycle.

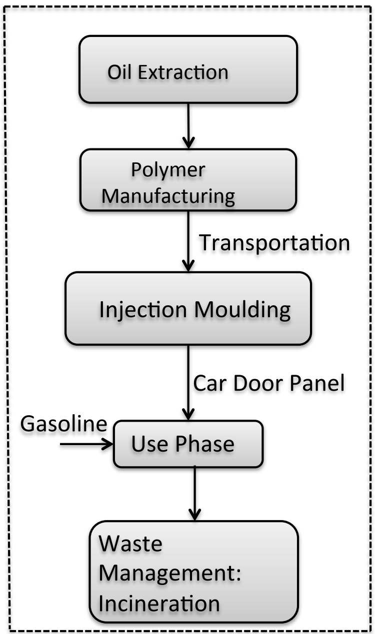

Figure 4: General simplified flowchart for the pure plastic (PP) based car door panels' lifecycle.

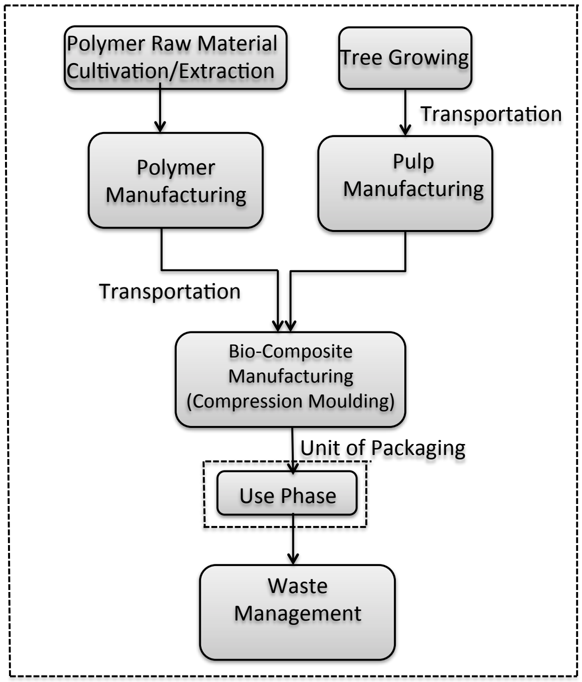

Figure 5: General and simplified flowchart for the bio-composite (DuraPulp and pulp mix) based packaging unit's lifecycle.

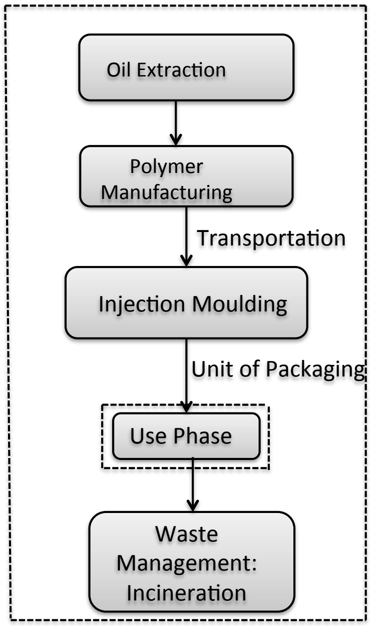

Figure 6: General and simplified flowchart pure plastic (PP and PS) based packaging unit's lifecycle.

4.1 Details of the different process steps

In this section, the different processes included in the life cycle of the materials are described in more detail.

4.1.1 Pulp Production Process

Data for the pulp manufacturing process is site specific for Södra. As for the wood flour for WPC, data for saw dust manufacturing is exported from the ecoinvent database.

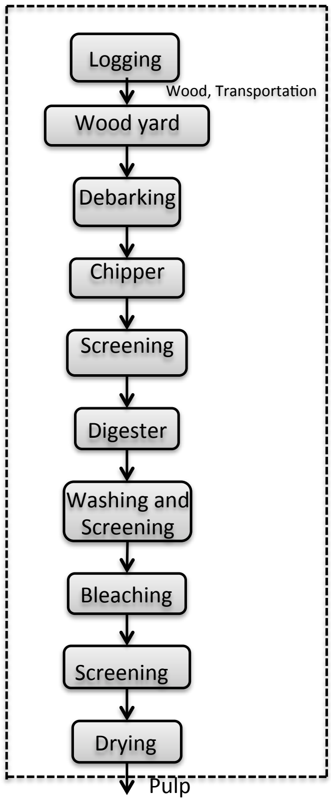

Figure 7: The pulp manufacturing process (Södra 2012)

Figure 7 shows the simplified manufacturing process for the pulp at Södra. First, the raw material, i.e. wood, is extracted from the forest through a process called logging. The wood is then transported on average for 80 km by trailer, 20 km by train and 47 km by boat from the extraction site to the pulping plant, and is then debarked. The bark is collected and used for heating. The logs are sent to the chipper and are cut up to the right size. Following this, the wood chips are screened and sorted after size and are then sent to the digester. In the digester the actual manufacturing of the pulp begins. The wood chips are mixed with cooking fluid, which is a mixture of black liquor and white liquor and the mix is heated with steam. After the digester, the pulp is sent to the washing and screening process. The wood chips that have not been fully digested are now removed. The first-rate fibres are separated from impurities such as twigs, sand and bark. Following this, the screened pulp is washed in order to separate the pulp from the black liquor. The removed black liquor is sent to energy recovery and for the recycling of chemicals. The pulp is then bleached in several steps. In the last phase of the pulp manufacturing process, drying, and the water is separated from the pulp (Södra 2012). The manufacturing of wood dust follows approximately the same processes until the chipper and screening, continuing with mechanical disintegration using disc refiners and drying. For inventory data, please see appendix A table A12.

4.1.2 Bio-based Polymer Manufacturing Processes

In this section, the details of the manufacturing processes for the bio-based polymers (i.e. PLA and bio-PE) are described. The datum for the PLA has been taken from the ecoinvent database. Data for bio-PE production have been partly taken from the ecoinvent database (ethanol production) and partly from Liptow and Tillman (2009) (i.e. energy use in e.g. polymerization). Data for PLA-REC have been taken from Vink et al. (2007)

4.1.2.1 Polylactic Acid Manufacturing Process

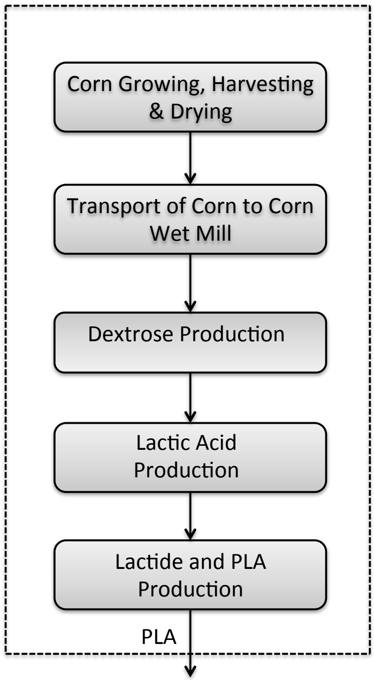

Figure 8: The polylactic acid manufacturing process. (Adapted from Vink et al. 2007)

The first step in the PLA manufacturing process is the cultivation, harvesting and drying of the corn. Here, the naturals input of solar energy, carbon dioxide and water are transformed into carbohydrates (e.g. starch and sugars). Following this, the corn is transported to the corn-wet mill for processing. The first phase of the processing is the dextrose production. The corn starch is first separated from other components, i.e. proteins, fats, fibres, ash and water. By using enzymes, the starch is hydrolysed into dextrose. Following this, the dextrose is transported by pipeline to the fermentation process, which converts the dextrose into lactic acid. In the final step, the high-weight PLA polymers are manufactured. (Vink et al. 2007)

4.1.2.2 Bio-Low Density Polyethylene Manufacturing Process

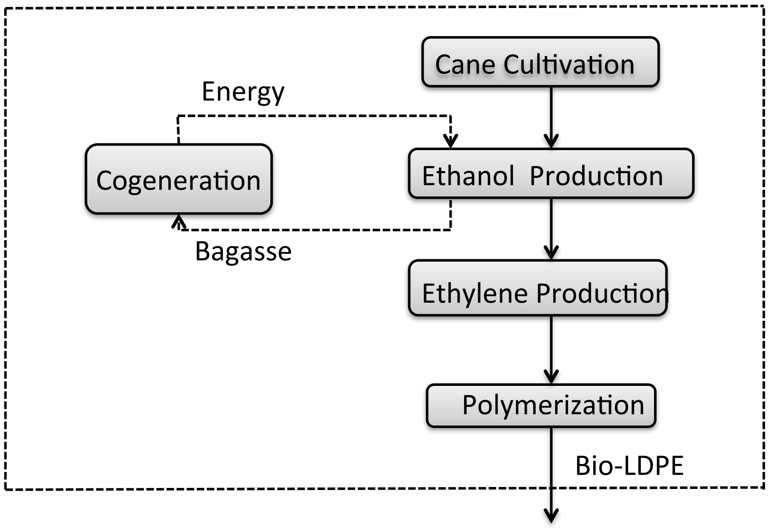

Figure 9: Accounting bio-LDPE manufacturing process from Brazilian sugarcane (adapted from Liptow and Tillman 2009)

The bio-PE is manufactured from sugar cane. After harvesting, the sugarcane is transported to an ethanol production plant, where it is washed and shredded. Following this is the extraction of the sugarcane juice and the bagasse recovery (cogeneration to recover energy). It is the extracted sugarcane juice that is treated in order to become ethanol. The ethanol manufacturing is finalized by the concentration and the purification. (Smeets et al. 2006) In the ethylene production, the ethanol is dehydrated and treated (e.g. washed and purified) in order to obtain ethylene (Barrocas and Lacerda 2007). The polymerization step of the manufacturing of the bio-LDPE is the same as for the fossil based LDPE (Liptow and Tillman 2009). This needs high pressure and high temperature (Plastics Europe 2008 b), and the polymerization takes place (Plastics Europe n.d. a).

4.1.3 Fossil-based Polymer Manufacturing Processes

In this section, the details of the manufacturing processes for the fossil based polymers (polypropylene (PP) and polystyrene (PS)) are described. The PP and PS processes and data are based on *Plastics Europe*'s PP (resin) manufacturing process and expandable PS manufacturing process, which includes foaming (all processes imported from ecoinvent database).

4.1.3.1 Polypropylene Production

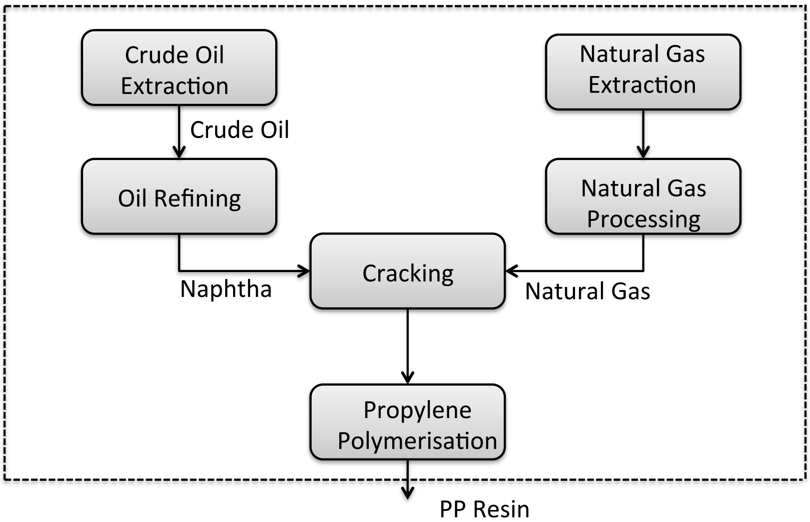

Figure 10: The polypropylene resin manufacturing process (Plastics Europe 2008 a)

Figure 10 shows the manufacturing process for PP resin. PP resin can be manufactured using two different techniques: *Liquid pool polymerisation* and *gas phase polymerisation,* the data used for this study is an average of these two manufacturing methods. The liquid pool polymerisation technique means that the polymer is produced in a liquid medium and for the gas phase polymerisation technique, the reactor works as a fluidised bed, with the polymers being stirred or passed by high-speed gas (Plastics Europe 2008 b). The process described in this study is a general way for plastics manufacturing, including the possibility of both techniques. In the crude oil extraction step, the oil is obtained by drilling into the earth. The crude oil is separated oil into hydrocarbon chains of different size, fractions, of which the fraction naphtha is essential for plastics production processes. In the cracker naphtha is broken down into smaller molecules: ethylene, propylene and butylene. The final step in the polypropylene resin manufacturing is the propylene polymerisation. This means that the different short hydrocarbon chains are linked together in order to create longer polymer chains (Plastics Europe n.d. a).

4.1.3.2 Polystyrene Production.

Specific description of the PS manufacturing phase is lacking from the plastics Europe, but the polymerization process is similar to the one described in 4.2.2.1 *Polypropylene Production.* The following step in the manufacturing process of polystyrene is foaming in which the polystyrene is expanded (not shown)

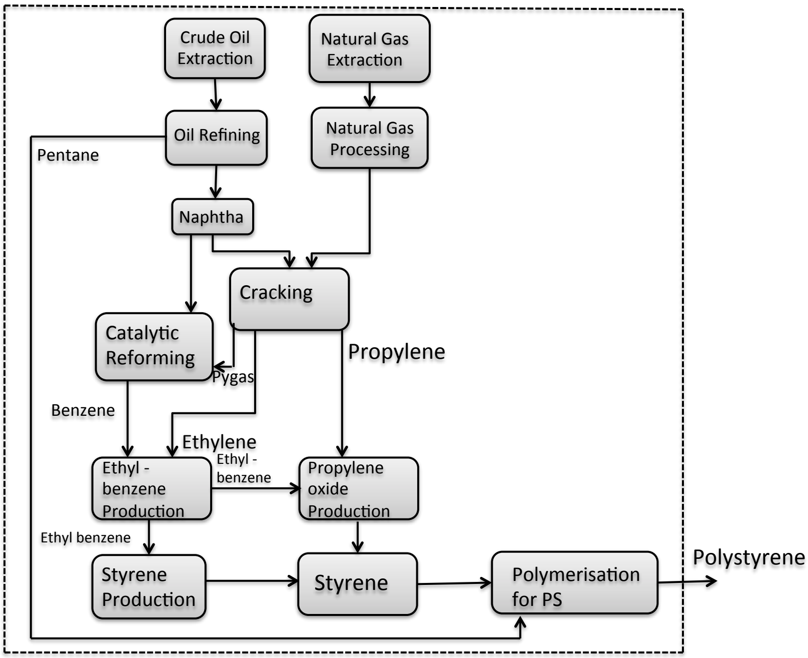

Figure 11: Flowchart for the manufacturing of polystyrene (Plastics Europe n.d. b)

4.1.4 Bio-Composite Manufacturing Processes

4.1.4.1 The Production of DuraPulp

The production method for DuraPulp and (assumed to be the same for pulp mix) has been developed by Södra, see figure 12. This is followed by a compression-moulding step for the bio-composites and an injection-moulding step for the pure polypropylene, polystyrene. Due to confidentiality, details on the DuraPulp manufacturing process will not be disclosed.

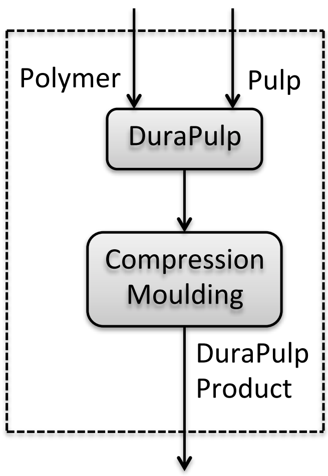

Figure 12: Flowchart of the DuraPulp manufacturing process.

In the first DuraPulp manufacturing step, the polymer fibre (i.e. the transformed polymer granulate) and the pulp are mixed together with the addition of chemicals by dissolving the polymer fibre in a tank of pulp fibres. The mixture is then dried in a counter current flash dryer and shaped into bales. The composition of DuraPulp after this step is 70% pulp and 30% polymer. Following this, the material is sent to the manufacturing plant of the actual product made from DuraPulp, which uses compression moulding. The DuraPulp is first turned into a sheet-form before entering the compression moulding process, in which the material is placed in an open, heated cavity. The open cavity is closed and heat and pressure are applied. Heat and pressure are applied until the material has cured and has solidified (Harper and Petrier 2003). The electricity use in this phase is 4.5 kwh/kg-moulded material (DuraPulp specific).

When manufacturing the WPC and FPC, there is an in-blend of 10% of the material (see Appendix B for details) output from the manufacturing process. The pure polypropylene, expandable polystyrene, WPC and FPC are assumed to be moulded by using the injection moulding technique, which consumes 3.4 kWh per kg moulded material (Thiriez and Gutowski 2006). For the moulding processes, Swedish electricity mix from the ecoinvent database is chosen. As for the manufacturing of polymers, site-specific electricity mixes are chosen from the ecoinvent database.

4.1.5 Use Phase and End of Life Treatment

The use phase for the car door panel can be found in figure 13, and is assumed to be an average European car (although use is assumed to take place in Sweden). The use phase for the packaging unit is excluded from this study. This is due to the fact that the use phase should be allocated to the content of the packaging unit, and not the packaging unit itself.

4.1.5.1 Use phase and End of Life: Car Door Panel

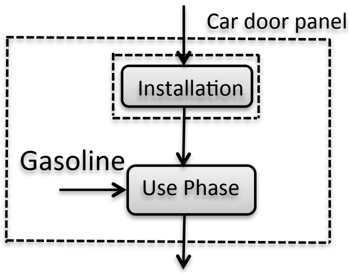

Figure 13: The use phase end of life for the car door panel, the red box showing the excluded installation phase.

The environmental impacts from the installation of the car door panel in the car are excluded from this study due to lack of data and the system boundary cut-off of personnel. Furthermore, the impacts from this step are assumed to be negligible. The use phase is included due to the environmental effect the fuel use the vehicle will have from the fuel needed for the transportation of one car door panel (See Appendix A for details). Since the lifespan of the car door panel is assumed to be the same as for a car, this life span is 17 years.

4.1.5.2 End of Life Treatment

The choice of waste management strategy for this study depends on the application of the material. In the application of the car door panel, all waste is assumed to be incinerated. This is due to the technique used when the cars are dismantled, where the parts that cannot be recycled or reused are shredded and sent to either landfill or incineration (Eionet n.d.). Since landfill not is a realistic long-term option for waste treatment due to legislations, incineration is chosen for the material that is not being recycled.

For the packaging unit, the material is assumed to be incinerated or sent to anaerobic digestion, depending on the ability of the material to biodegrade (i.e. for DuraPulp: PLA/PLA-REC). Data for end of life treatments were taken from the ecoinvent database (incineration and anaerobic digestion). Pulp is represented by the incineration of packaging cardboard and PLA by mixed plastic waste (Madival et al. 2009) due to a lack of specific data. The methane produced in the anaerobic digestion is assumed to be burned rather than emitted, although the heat and energy gained from this is not included.

4.1.6 Recycling Scenario

4.1.6.1 Recycling of the Packaging Unit

In the recycling process, the polymer fraction in the material (DuraPulp and pulp mix) is changed from 30% polymer and 70% pulp to 60% polymer and 40% pulp; the yield in the recycling process is assumed to be 90%. After the second use, the material is continued to be recycled and it is assumed that there are no losses in this stream. After the final use of the product, it is sent to waste treatment, either incineration or anaerobic digestion.

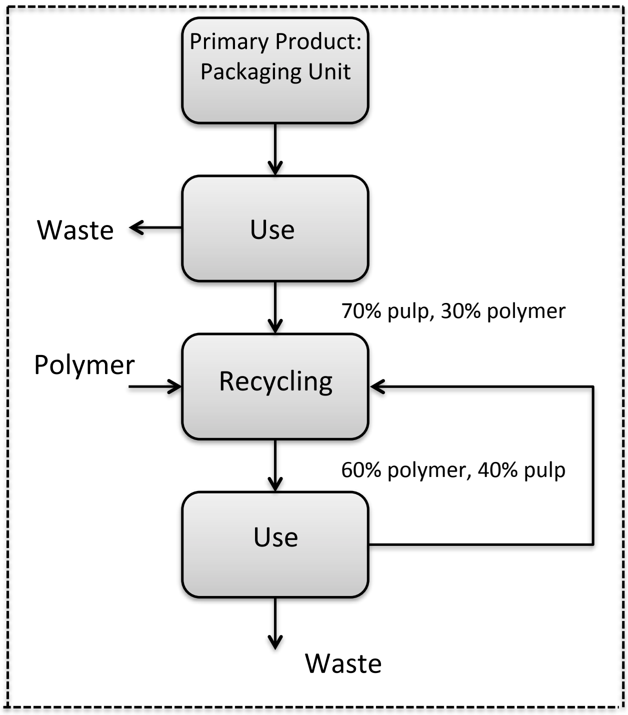

Figure 14: The recycling process for the short lifespan processes.

4.2 Life Cycle Inventory Results

Table 1 shows the main flows for the manufacturing the materials considered in this study. The emission data and resource use is only available for DuraPulp: PLA and includes the resources used in PLA and pulp manufacturing (wood and corn not included). Due to confidentiality specific chemicals and the origin of the used energy will not be shown. Specific inventory data used for the modelling of the Södra pulp manufacturing can be found in Appendix A table A12.

Table 1: The main flows of chemicals fuels and emissions connected to the manufacturing per kg of bio-composite

<table>
<tr><th>Inputs</th><th>D:PLA</th><th>D:PLAR</th><th>PM:PE</th><th>PM:PP</th><th>WPC</th><th>FPC</th><th>PP</th><th>PS</th></tr>
<tr><td>Fibre
kg</td><td colspan="4">0.7</td><td>0.5</td><td>0.4</td><td colspan="2">0</td></tr>
<tr><td>Polymer
kg</td><td colspan="4">0.3</td><td>0.5</td><td>0.6</td><td colspan="2">1</td></tr>
<tr><td>Chemicals
kwh</td><td>0.226</td><td colspan="7">n/a</td></tr>
<tr><td>Fuel
kwh</td><td>7.5</td><td colspan="7">n/a</td></tr>
<tr><td>Electricity
kwh</td><td>4.62</td><td colspan="3">4.5</td><td colspan="4">3.4</td></tr>
<tr><td>Water
liter</td><td>78</td><td colspan="7">n/a</td></tr>
<tr><td>Outputs</td><td colspan="8">Per kg manufactured material</td></tr>
<tr><td>Material
kg</td><td colspan="8">1</td></tr>
<tr><td colspan="9">Emissions toWater</td></tr>
<tr><td>TOC
kg</td><td>0.0061</td><td colspan="7">n/a</td></tr>
<tr><td>Total Nitrogen
kg</td><td>0.0003</td><td colspan="7">n/a</td></tr>
<tr><td>Total Phospho-rous
kg</td><td>0.00002</td><td colspan="7">n/a</td></tr>
<tr><td colspan="9">Emissions to Air</td></tr>
<tr><td>Sulphur
kg</td><td>0.00015</td><td colspan="7">n/a</td></tr>
<tr><td>Hydrogen Sulphur
kg</td><td>0.00001</td><td colspan="7">n/a</td></tr>
</table>

Nitrogen Oxides kg	0.0013	n/a
Dust kg	0,0002 5	n/a n
CarbonDioxide kg	0.360	n/a
Solid waste to landfill	0.012 kg	n/a

Table 1 shows the main inputs and outputs from the different manufacturing processes for manufacturing 1 kg of the bio-composites that are being applied in the car door panel and the packaging unit. The main differences are the amount of polymer added to the product, ranging from 30% in the DuraPulp and pulp mix material to 100% in the pure virgin plastic cases. The second major difference is the input of electricity. This is due to the choice of different moulding techniques, with DuraPulp and pulp mix being compression moulded and the other materials being injection moulded.

5. Results of the Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) describes the impacts of the environmental loads that are accounted for in the inventory analysis. This phase of the LCA includes the classification (i.e. the sorting of inventory parameters according to the type of environmental impacts) and the characterization (the relative contribution of the emissions to the environmental impacts) (Baumann and Tillman 2004).

5.1 Characterization Results

The following section will show the results from the LCIA of the car door panel and the packaging unit where no recycling occurs and the manufacturing of the bio-composite takes place in Sweden.

5.1.1 Car Door Panel

The results shown in figure 15-19 all follow the same trend, with the life cycle impacts being dominated by the use phase due to weights and the pure virgin polypropylene are dominant in all impact categories. Therefor, extended discussions regarding the use phase are not included for the different impact categories, but are nevertheless applicable to all car door panel cases, and only category specific information are further included in this section. See table A1 and A2 in Appendix A for details on weights of the materials for the car door panels.

5.1.1.1 Global Warming Potential

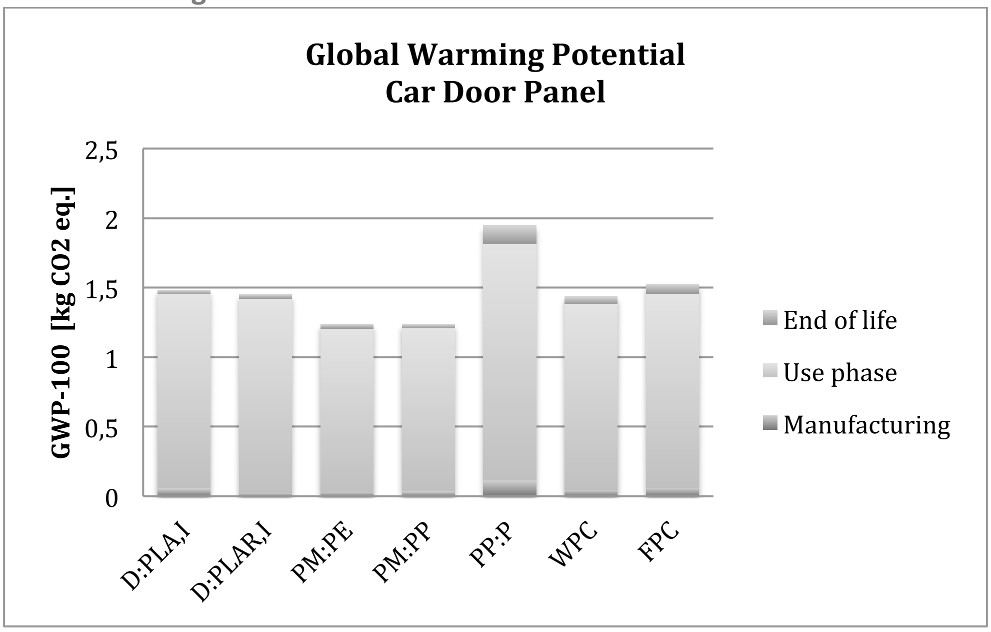

Figure 15: The impacts on climate change (GWP 100) for the car door panel shown for the different life phases measured in kg CO_2 eq.

5.1.1.2 Eutrophication Potential

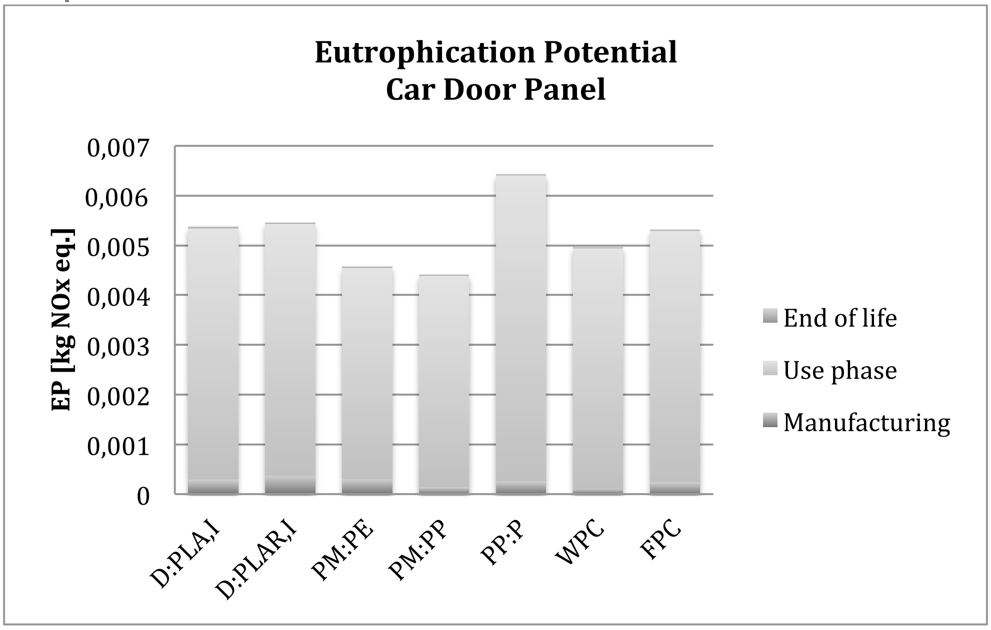

Figure 16. The eutrophication potential (European average) for the car door panel shown for the different life phases measured in kg NO_x eq.

5.1.1.3 Acidification Potential

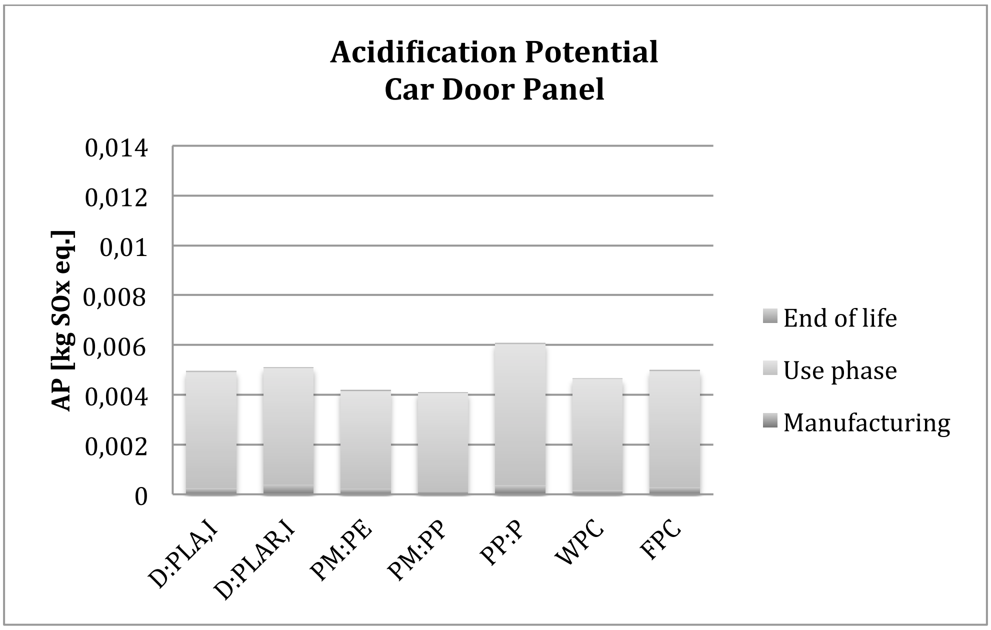

Figure 17: The acidification potential (European average) for the car door panel shown for the different life phases measured in SO_x equivalents.

5.1.1.4 Photochemical Ozone Creation Potential

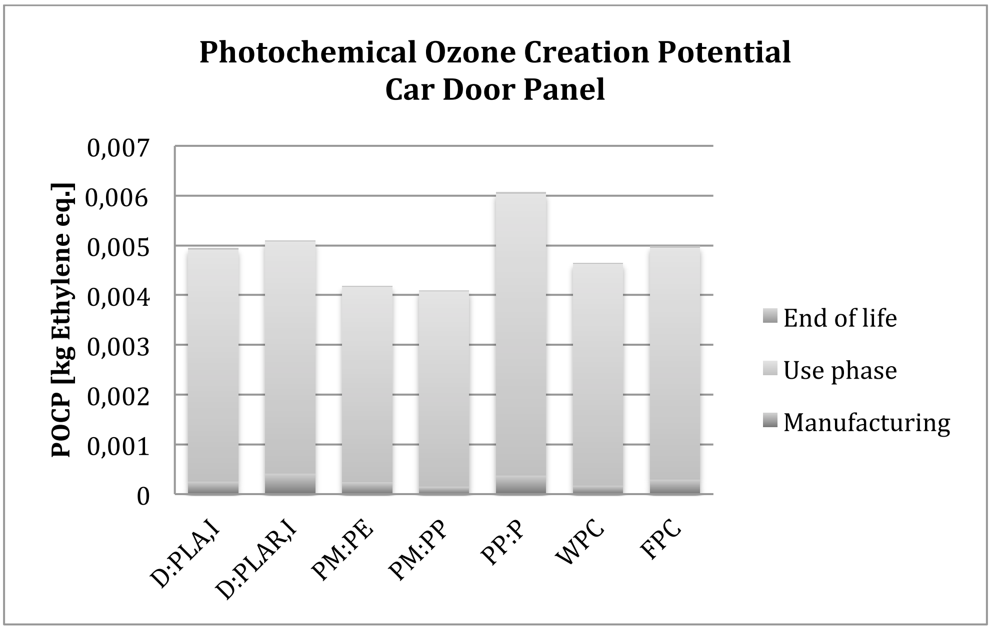

Figure 18: The photochemical ozone creation potential (high NO_x) for the car door panel shown for the different phases of the life cycle measured in kg ethylene eq.

Among the biopolymers, the fuel used to manufacture PLA-REC (i.e. the use of natural gas according to the inventory in Vink et al. 2007) also contributes to the POCP category compared to the manufacturing impacts of PLA and bio-PE.

5.1.1.5 Depletion of Abiotic Resources

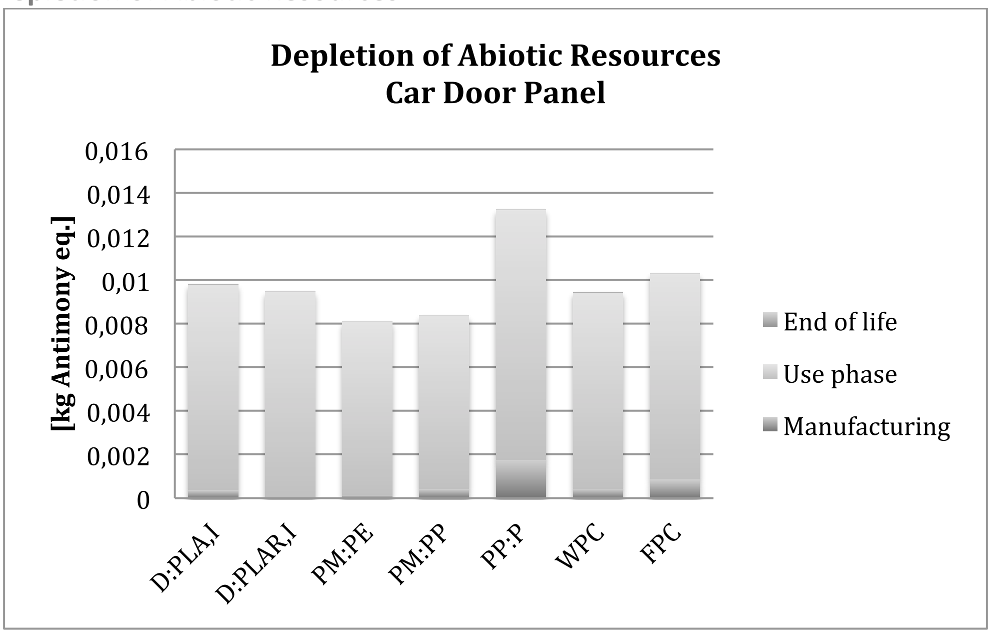

Figure 19: The abiotic resource depletion (resource use) for the car door panel shown for the different phases of the life cycle measured in kg antimony eq.

For this category the manufacturing pure plastic case has a greater environmental impact than the other materials. This is because the raw material for polypropylene is crude oil or natural gas, i.e. non-renewable.

5.1.2 Packaging Unit

5.1.2.1 Global Warming Potential

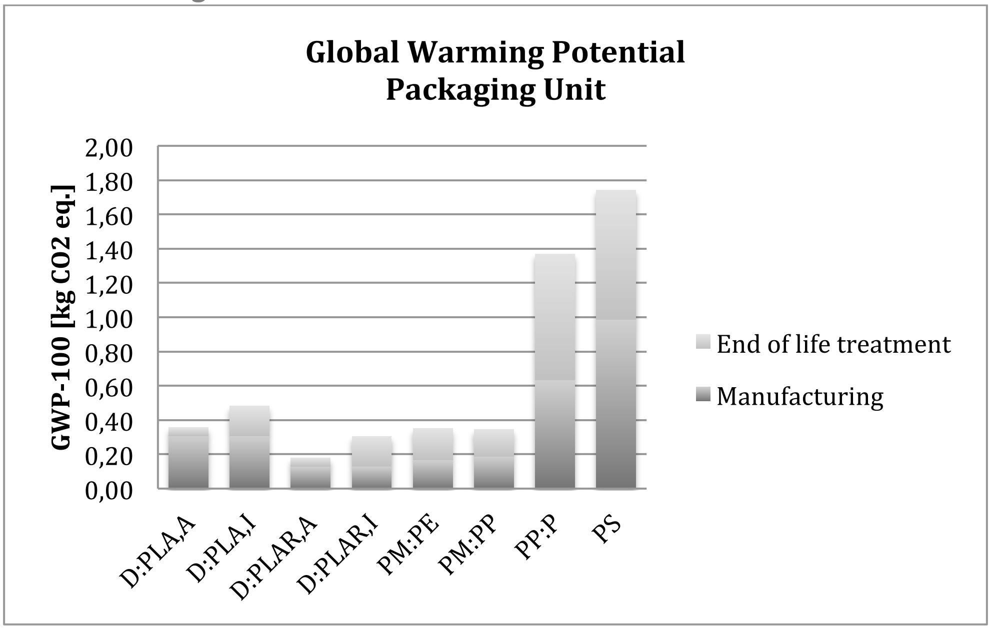

Figure 20: The impacts on climate change (GWP 100) for the packaging shown for the different life phases measured in kg CO_2 eq.

More than half of the global warming potential comes from the manufacturing phase for the packaging unit. This has mainly to do with the amount of virgin polymer added to the bio-composite (and pure plastic cases). The virgin polymers global warming potential depends predominantly on the manufacturing process and its location, but also somewhat on them being bio based or fossil based. For example, PLA is manufactured using UCTE electricity mix (according to the ecoinvent database), which emits 0.52 kg CO_2 eq./kWh, while bio-PE is manufactured using Brazilian electricity mix (PE is assumed to be manufactured in Brazil) which emits 0.22 kg CO_2 eq. /kWh. This will have an impact on the global warming potential of the manufacturing phase, as 1 kWh of the UCTE electricity mix emits approximately 2.4 times more CO_2 eq. compared to 1 kWh of the Brazilian mix. Moreover, the manufacturer of PLA-REC has offset greenhouse gas emissions by buying renewable energy in the equivalent quantity of the electricity used in the manufacturing process (Vink et al. 2007), lowering the over all global warming potential for the DuraPulp: PLA-REC compared to conventional PLA.

Additionally, the end of life treatment also has a significant effect on the global warming potential for the packaging unit, the reason for this is the emission of carbon (that has been stored in the material) that occurs when plastics are incinerated that leads to the high contribution to the global warming potential. The incinerated bio-composites contribute more to the global warming potential compared to the bio-composites being sent to anaerobic digestion. The incinerations of the pure PP and PS have the largest impact. This is partly due to the increased weight of the packaging unit and due to the fact that there is no blend in of pulp, which lowers the global warming potential of the end of life treatment for the material.

5.1.2.2 Eutrophication Potential

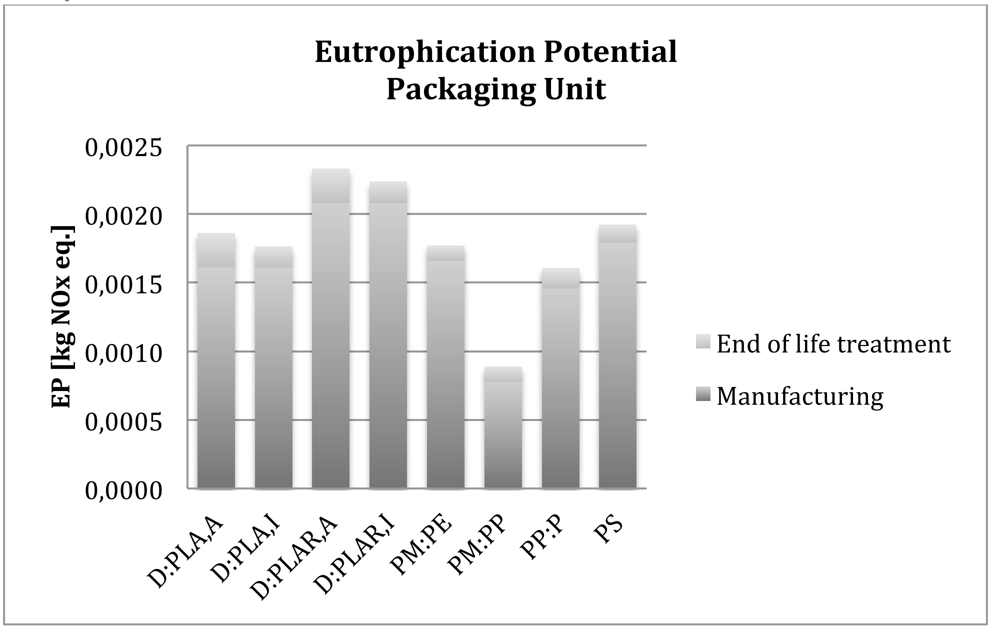

Figure 21: The impact on eutrophication potential (European average) for the packaging unit measured in kg NO_x eq.

The eutrophication potential is higher for the bio-based polymers than for the fossil-based polymers. Moreover, when comparing the bio-based polymers, bio-PE has a higher eutrophication potential than PLA. This is the result of the use of fertilizers connected to the biomass cultivation process. Generally, for 1 litre of ethanol (from which the ethylene is manufactured), 12.3 kg of sugar cane is needed (Monteiro et Al. 2010). This amount of biomass is compared to the 2.5 kg of corn that is needed for the manufacturing of 1 kg of PLA (Kingsland 2010). The raw material for polypropylene does not need fertilizers, which lowers the eutrophication potential during the manufacturing phase. Also the wood used when manufacturing pulp is not fertilized. The higher eutrophication potential for the DuraPulp: PLA-REC compared to PLA comes from the manufacturing process, although specific details have not been identified (PLA-REC is the new generation PLA).

5.1.2.3 Acidification Potential

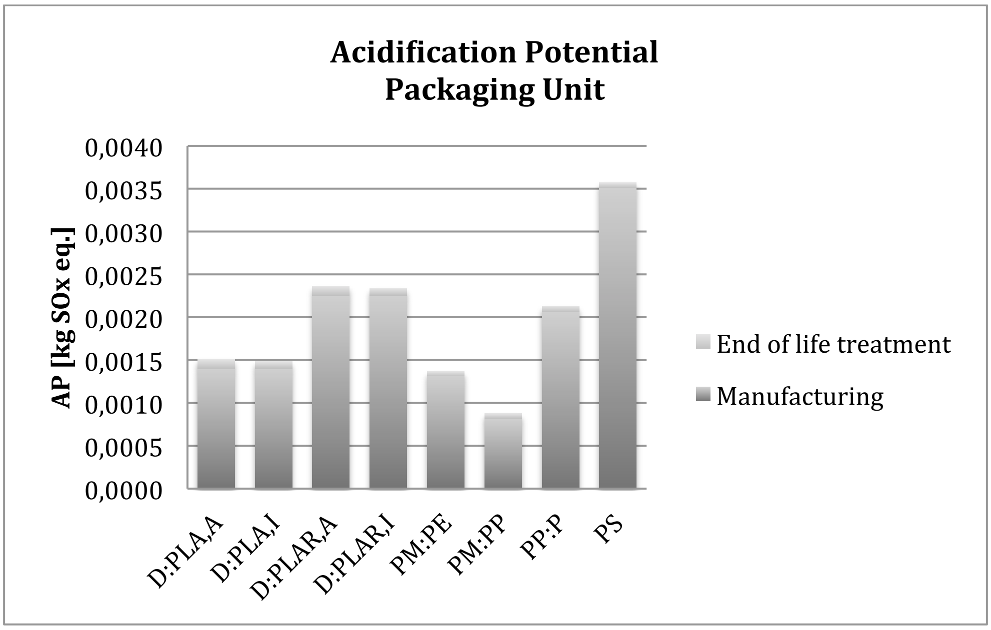

Figure 22. The impact on acidification potential (European average) for the packaging unit measured in SO_x equivalents.

The fuel and electricity used when manufacturing polymer has a big influence on the packaging unit's acidification potential. The polystyrene case has the highest acidification potential due to its chemical properties. Among the bio-based polymer cases, the DuraPulp: PLA-REC scenarios have the highest contribution. This is due to the use of natural gas in the manufacturing process. The bio-based materials that are sent to anaerobic digestion have a slightly higher acidification potential than the incinerated of the same kind due to the formation of acids by the bacteria in the anaerobic process (Van Haandel& Van Der Lubbe 2007). The increased acidification potential for the pulp mix: bio-PE packaging unit compared the pulp mix: PP packaging unit is due to the increased acidic emissions in connection to the ethanol fermentation and transportation across the Atlantic Ocean (this also applies to the pulp mix: bio-PE car door panel, although this is not as noticeable due to the impact from the use phase).

5.1.2.4 Photochemical Ozone Creation Potential

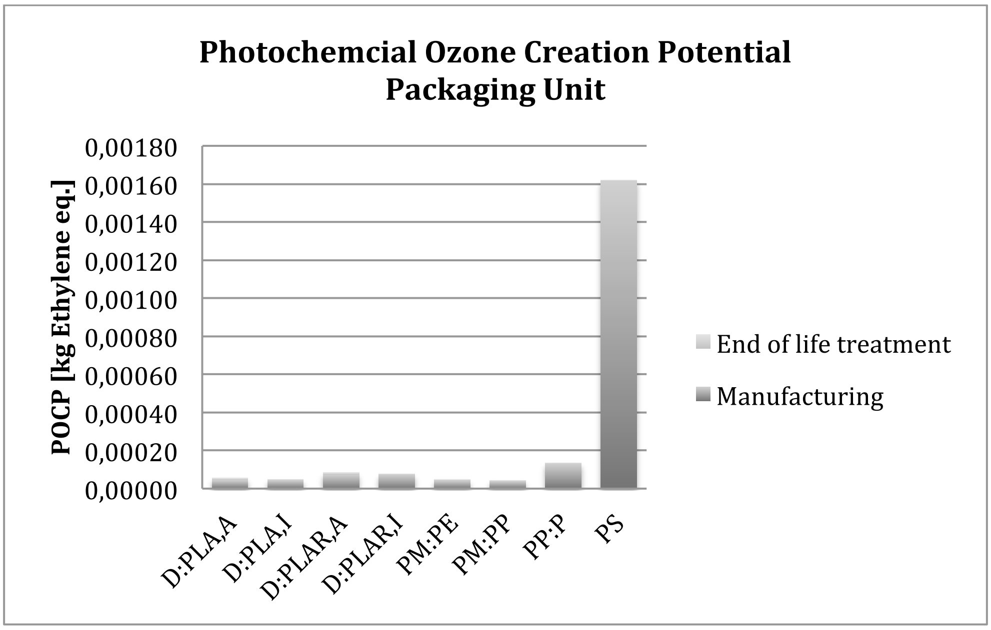

Figure 23: The impact on photochemical ozone creation potential (high NOx) for the packaging unit measured in kg ethylene eq.

The case when polystyrene is used is contributing the most to this category, which is consistent to the other impact categories. This is due to the benzene and other chemicals used in the PS-manufacturing phase and the pentane used in the foaming process. DuraPulp: PLA-REC contributes most of the bio-composites in this impact category as a consequence of the natural gas used in the PLA-REC manufacturing phase.

5.1.2.5 Depletion of Abiotic Resources

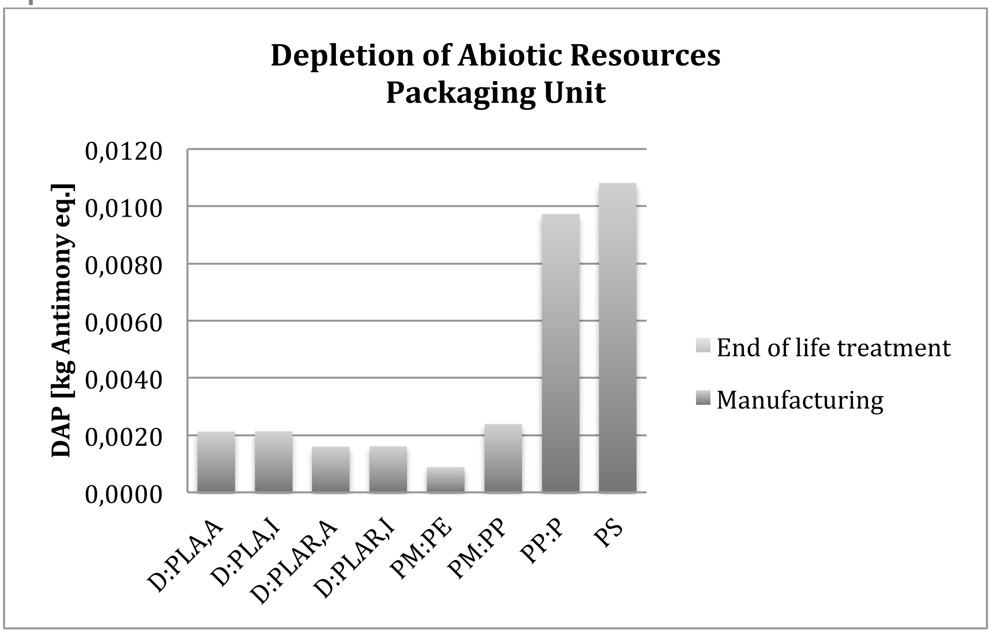

Figure 24: Depletion of abiotic resources (resource use) for the packaging unit measured in kg antimony eq.

The choice of fossil-polymer has a large influence on the depletion of abiotic resources category for the packaging unit. Moreover, in consistency with the global warming potential, the electricity grid mix has a big impact in this category. The manufacturing of bio-PE takes place in Brazil and therefor a Brazilian electricity mix is used. The energy consumption in Brazil consists of 39% "oil and other liquids", and about 50% renewables (EIA 2012), and the amount of antimony equivalents, which is the unit depletion of abiotic resources is measured in, is 0.00058 kg/kWh. The PLA is assumed to be manufactured using the UCTE electricity mix, which is average European electricity (both exported from the ecoinvent database), and the amount of antimony equivalents is 0.00382 kg/kWh, this is 6.6 times more intense per kWh in the depletion of abiotic resources category compared to the Brazilian electricity mix. PLA-REC includes the purchasing of renewable energy certificates, which offsets some of the impacts for this category. The renewable energy certificates (which correspond to wind derived electricity) are purchased by Natureworks, who manufacture the PLA-REC, in the equivalent quantity of the electricity used in the manufacturing process (Vink et al. 2007). This leads to a purchased decrease in the use of fossil energy for the manufacturing of PLA and therefor decreasing its contribution to this impact category.

5.2 Summary of LCIA Results

The LCIA shows that for the car door panel, the DuraPulp: PLA is often outperformed by the pulp mix: bio-PE and pulp mix: PP. This is due to the lower mass of the car door panels manufactured from the latter materials (see Appendix A, table A1 for densities) and the decreased use of fuels in the use phase. All the impact categories follow the same trend where the DuraPulp: PLA is outperformed by the pulp mix: bio-PE and pulp mix: PP. It is also obvious that for all categories, the use phase has the largest influence on the environment. As for the packaging unit, the DuraPulp and pulp mix cases outperform the pure virgin plastic cases in all categories except for the eutrophication potential category. The main reason for this is the use of fertilizers in the cultivation phase. An impact that influences the environmental impact for the DuraPulp and pulp mix packaging unit significantly is the manufacturing site for the polymer which affects the electricity mix as well as the fuels used in the manufacturing process, an example of this is the global warming potential and depletion of abiotic resources for PLA-REC compared to PLA.

When comparing the two different applications of DuraPulp: PLA (incinerated) and pulp mix: bio-PE to pure virgin polypropylene, it is concluded the application offsetting the most environmental impact is the packaging unit, except for the eutrophication potential of the packaging unit, where a pure plastic packaging unit is preferred over the Durapulp: PLA and pulp mix: bio-PE, see table 2 and 3 for numbers. The relative impacts have been calculated using equation (1). The three materials are chosen due to the fact that they are the only materials used in both applications. It must be noticed, that in the packaging unit case, the use phase is passive compared to the car door panel's use phase, which is considered active. This might make the real life comparison between the two applications problematic.

$$Relative\ Impact = \frac{Impact\ PP{:}\ P}{Impact\ DuraPulp} \tag{1}$$

Table 2: Factors for comparing the long lifespan scenario product (car door panel) and the short lifespan scenario product (packaging unit) for the DuraPulp: PLA incinerated and pure polypropylene.

Impact Category	Car Door Panel	Packaging Unit
Global Warming Potential	1.31	2.84
Eutrophication Potential	1.20	0.91
Acidification Potential	1.23	1.44
Photochemical Ozone Creation Potential	1.25	2.84
Abiotic Resource Depletion	1.35	4.56

Table 3: Factors for comparing the long lifespan scenario product (car door panel) and the short lifespan scenario product (packaging unit) for the pulp mix: bio-PE and the pure polypropylene.

Impact Category	Car Door Panel	Packaging Unit
Global Warming Potential	1.34	3.90
Eutrophication Potential	1.41	0.91
Acidification Potential	1.45	1.56
Photochemical Ozone Creation Potential	1.48	2.84
Abiotic Resource Depletion	1.63	11

6. Scenario Analysis

6.1. How the Collection Rate affects total Lifecycle Impact for Packaging Unit

In figure 26, the impacts from a varying waste collection rate for the packaging unit can be found. In the recycling process of the bio-composites, the polymer fraction changes from 30% to 60%. The figure shows the allocated impact allocated to the primary (first time use) and secondary products (all other uses) for 100% recycling (all is collected and sent to recycling) and 50% recycling as well as 0% recycling. The allocation is done in order to divide the overall life cycle impacts between the primary and secondary product system since recycling probably will lead to a lower impact per single product.

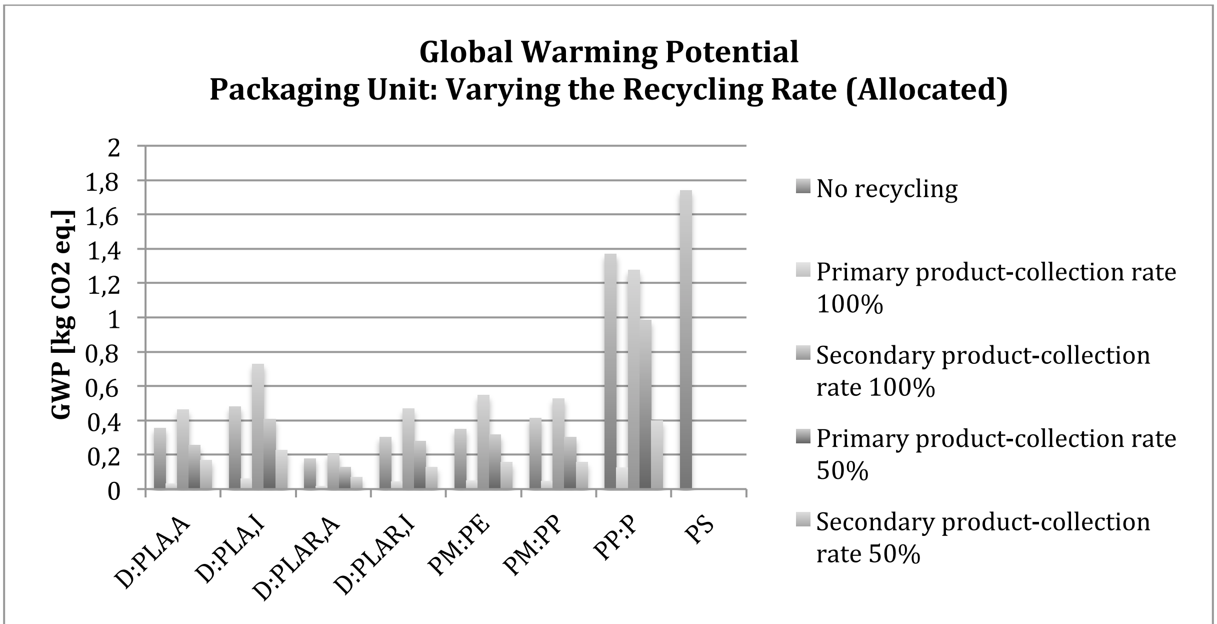

Figure 26: The allocated impacts on climate change for 0% recycling, 100% recycling and 50% recycling.

The results in figure 26 are allocated according to ISO/TR 14049 (ISO 14049 2000). Varying the collection rate shows that a higher collection rate gives a higher impact for the secondary product. This is due to the allocation factors and the addition of polymers in the recycling process. In the case of a collection rate of 100%, the primary product allocation factor is 9% and the secondary product allocation factor is 91 % and in the case of 50% collection rate, 72% of the total impact is allocated to the primary product and 28% is allocated to the secondary product (see Appendix A for details and calculations).

The global warming potential is higher for the recycled fossil based polymers, which is connected to the input of virgin polymers in the recycling process. This is also applicable to the acidification potential, photochemical ozone creation potential and depletion of abiotic resources (not shown). As for the eutrophication potential (not shown), the biopolymers have a higher eutrophication potential than the composite based on fossil-polymer and the pure polypropylene.

The allocation in figure 26 shows that recycling has a positive impact on the first time use of the product. What the figures fail to reveal is the actual number of uses, which is higher for the higher collection rate. To the secondary product, the impact from recycling is added (i.e. the addition of virgin polymer and electricity). The amount of virgin polymer added increases with the collection rate (more polymer is needed to change the composition of the material). This means that there is a trade-off between the addition of new polymer and the collection rate in order for the secondary product to have less impact than the product not being recycled at all. The figure shows that compared to polystyrene and polypropylene, the DuraPulp: PLA can be used a number of times without being recycled until the environmental impacts are added up to the same amount as for the pure virgin plastic case (between approximately 3 to 4 times depending on the end of life treatment). In order to decrease the environmental impacts from the DuraPulp and pulp mix recycling process, a lower input of virgin polymer (either being fossil based or bio based depending on the polymer in the matrix) in the recycling process is needed. This can be achieved either by lowering the collection rate or by further research in developing the recycling process.

6.2 How the Manufacturing Site Affects the Total Lifecycle Impact

6.2.1 Impacts Depending on Moulding Location for the Packaging Unit

Figure 27 shows the global warming potential for the packaging unit where the moulding of the product takes place in either Europe or Sweden. Only the change in the used electricity mix during the moulding process is taken into account.

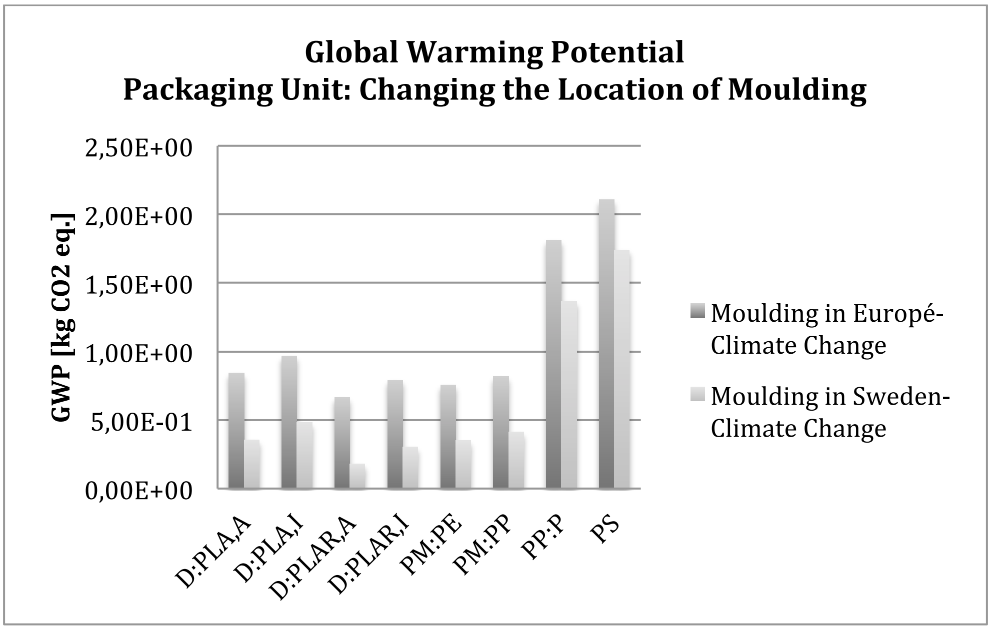

Figure 27: Impacts on the climate change for the packaging unit depending on the moulding site (Europe vs. Sweden).

Figure 27 shows that it is important to be careful when choosing the site for the moulding when considering the global warming potential. The eutrophication potential, acidification potential, photochemical ozone creation potential and the depletion of abiotic resources follow the same trend (not shown).

6.2.2 Impacts from Location of Manufacturing Polypropylene for the Pulp Mix: PP in the Application of the Car Door Panel

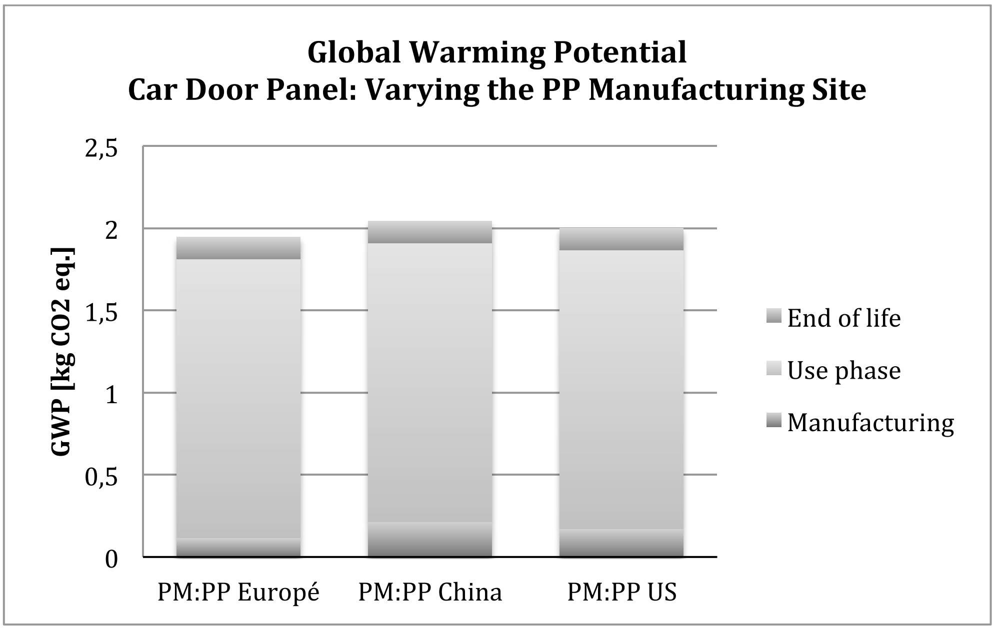

Figure 28: How the total impacts for the climate change for the lifecycle changes for the pulp mix: PP when choosing polypropylene manufactured in Europe, China or the US.

Figure 28 shows that the difference in global warming potential depending on manufacturing location of polypropylene for the pulp mix: PP based car door panel is small due to the dominance of the use phase. Eutrophication potential, acidification potential, photochemical ozone creation potential and depletion of abiotic resources follow the same trend (not shown).

Figure 27 and 28 show that the location for manufacturing has more influence for the short lifespan product compared to the long lifespan product, where the use phase has a large influence on the life cycle impact.

6.3 How the Use Phase Affects Total Lifecycle Impact for the Car Door Panel

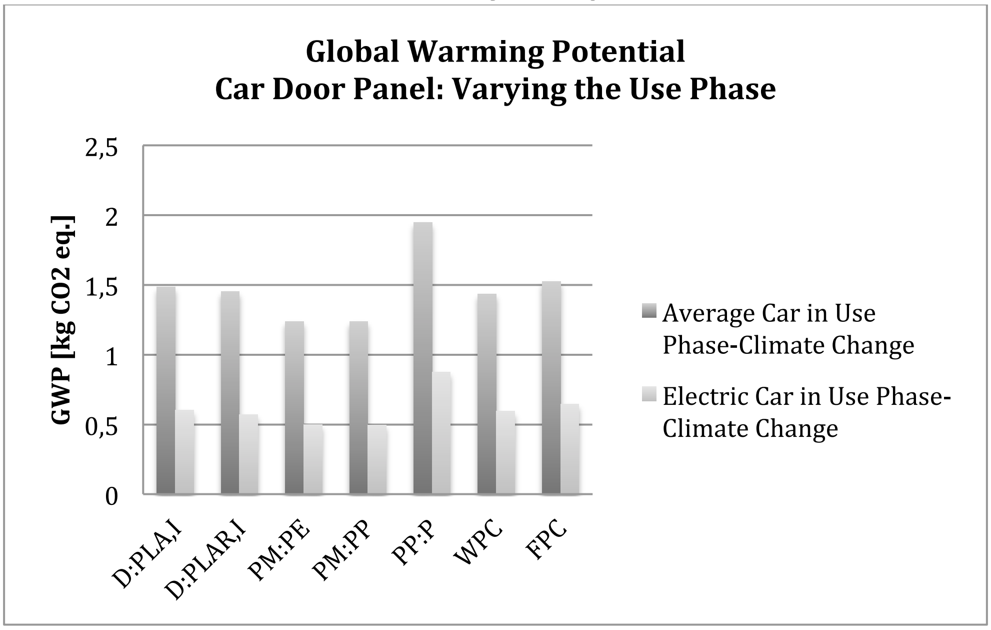

Figure 29: The impact on climate change for the car door panel installed in an electric car compared to an average car.

Figure 29 shows that the impact from the use phase decreases significantly when choosing an electric car instead of an average car. The electric car is an average European electric car and the average car is a European average car running on gasoline, both imported from the ecoinvent database. This means that the share of the impact from the manufacturing of the actual car door panel is increased; the global warming potential for the average car is about 2.7 times higher than for the electric car. This implies that in order to decrease the overall environmental impact of the car door panel, another use phase should be chosen. The eutrophication potential, acidification potential, photochemical ozone creation potential and depletion of abiotic resources (not shown) follow the same trend.

6.4 How the Polymer Fraction has Effect on the Use Phase and Total Lifecycle for the Car Door Panel

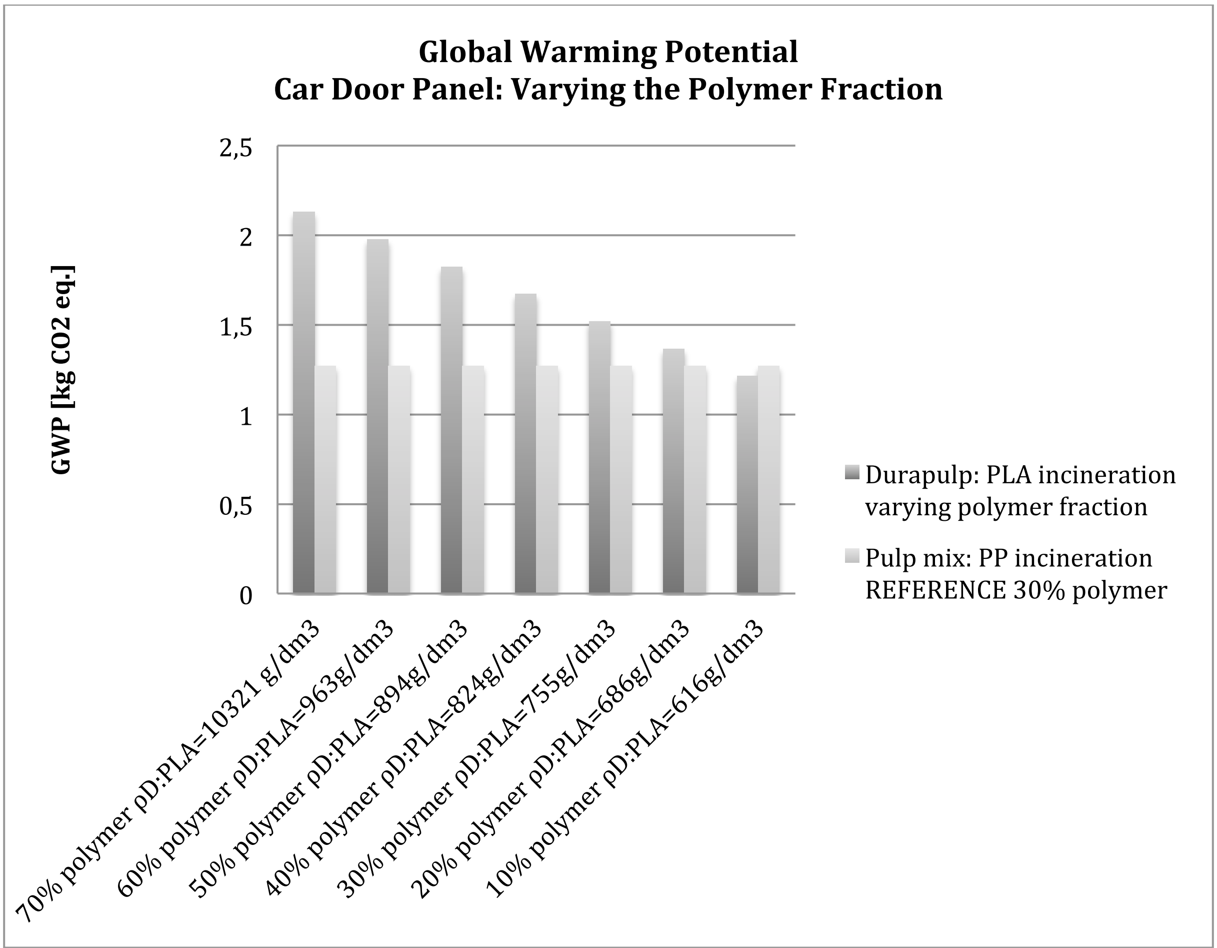

Figure 30: How a decreased PLA share in the DuraPulp has effect on the global warming potential for the entire life cycle.

The results in figure 30 shows that a decreased share of PLA decreases the environmental load of the material. This is mainly due to the decreased weight of the car door panel, which leads to a lower fuel use. For the DuraPulp: PLA material to be equal to pulp mix: PP 30% polymer and 70% pulp, PLA share of around 15% is required. The eutrophication potential, acidification potential, photochemical ozone creation potential and depletion of abiotic resources (not shown) follow the same trend.

7. Synthesis of Results and Conclusion

When considering the characterized results for the car door panel, it is obvious that the main contributing stage of the life cycle is the use phase, which is true for all impact categories. This means that in the case of the car door panel, the choice of a bio-composite will contribute to a decrease in environmental impact compared to a car door panel made from pure plastic. This is due to the fact that the weight of the car door panel has a very significant influence on the total environmental impacts connected to it, since it affects the amount of fuel consumed in the use phase. As for the DuraPulp and pulp mix material, which consists of 30% polymer and 70% pulp, DuraPulp: PLA is outperformed by pulp mix: bio-PE and pulp mix: PP due to a lower amount of fuel combustion during the use phase as a consequence of the lower density of PP and PE.

For the packaging unit, the characterized results show that the manufacturing phase of the bio-composites based on biopolymers contribute significantly more to the eutrophication category compared to the bio-composites based on fossil polymers. For this application, the characterized results also show that the environmental impacts for DuraPulp: PLA sent to anaerobic digestion and pulp mix: bio-PE are in most cases close to equal, concluding that if DuraPulp: PLA is to be preferred, a strong incentive for the consumer to sort the household waste (i.e. in this case, to send to anaerobic digestion) is needed. If this is not the case, it may be preferable to substitute the PLA for bio-PE. The pure plastic cases are contributing the most to the environmental impact categories primarily due to the higher input of virgin polymers compared to DuraPulp and pulp mixes. The results also show that the manufacturing site and fuel used in the manufacturing phase for the DuraPulp and pulp mix materials has a large influence on the different impact categories. This is especially obvious in the acidification and photochemical ozone creation potential categories, where the use of natural gas during the DuraPulp: PLA-REC manufacturing leads to a high potential for both.

When comparing the impacts from the car door panel to the packaging unit, it can be concluded that incinerated DuraPulp: PLA and pulp mix: bio-PE set against pure virgin polypropylene will offset the most environmental impact in the packaging unit application (see table 2 and 3). This indicates that the short lifespan product may be the most sustainable application for DuraPulp, even though it still decreases the overall emissions in both applications.

The recycling process contributes significantly to the DuraPulp and pulp mix packaging unit's environmental life cycle impact due to the addition of virgin polymer in the recycling process. This means that it is preferable to aim for a decreased need of adding virgin polymers when recycling DuraPulp and pulp mix. Additionally, since the polymer:pulp ratio is only changed the first time the material is recycled, it is important to keep recycling the already recycled material. If this is not a probable case, the intent of recycling the material in the first case may be questioned, as it may be more efficient sending the material to incineration or anaerobic digestion instead (depending on the collection rate) or aim for a reuse scenario. Furthermore, for the packaging unit, the choice of manufacturing method and location is of importance in order to decrease the environmental impacts. Compression moulding generally requires 4.5 kWh per kg of material, while injection moulding requires on average 3.4 kWh per kg material (Thiriez and Gutowski 2006). If the material is being moulded in Sweden, this will not influence the environmental impacts of the product significantly, due to a renewable energy mix, but if the material is being manufactured using average European electricity mix this will have a substantial effect. Similarly, the impacts of the polymers depend on the location of manufacturing, which may indicated that it is preferable to choose a fossil-polymer manufactured with renewable electricity mix than a biopolymer manufactured with using a non-renewable electricity mix. When considering the car door panel, the manufacturing site does not matter as much due to the huge influence of the use phase, although here is where the manufacturer has the opportunity of making an impact so a careful choice of origin for the polymers is still recommended.

The different scenarios show that the input of virgin polymers (i.e. not previously used polymers) has a large influence on the environmental impact categories. In the car door panel application, the fraction of polymer in the bio-composite must either be decreased from 30% polymer to about 15% polymer (primarily due to weight), or a polymer of lower density must be chosen instead; for example bio-PE instead of PLA in order for a pulp mix with the DuraPulp ratio based on a bio-polymer to be environmentally favourable over pulp mix: PP. Another way of affecting the environmental impact of the car door panel would be to change the use phase (apply it in an electric car), a task that in reality may be hard to accomplish. Additionally, there is no recycling of the car door panel. This is due to the fact that when the car is dismantled, the fluff (i.e. the shredded material not being recycled, such as seats and car door panels made out of bio-composite) is sent to either incineration to recover energy or for landfill on distance (Jensen et al. 2012).

As for methodological choices, no system expansion is performed when considering the end of life treatment in this study and the energy gains are not taken into account. This is due to the fact that the attributional LCA method is chosen. The choice of the methodology is originating in the definitions of the goals of the study and the way that they are defined. Nevertheless, the heat released when the material is sent to incineration, as well as the offset of fossil methane by bio-methane gained in anaerobic digestion can be accounted for. This means that the environmental impacts of the materials would likely be higher in this study than if there would be a system expansion.

When investigating which application for a material that is preferred between a short lifespan product and a long lifespan product, a normalized reference flow on the basis of life length is required. For this study, the life length of the durable product is 17 years and the life length of the recyclable product is 1 month. The normalization is done in order to take into account the lower input of raw material for the long lifespan product and the increased input of material for the short lifespan product due to a higher product turnover rate. The point of this is to illustrate the different need in raw material extraction depending on life length and application and to enable a more fair quantitative comparison. An increased life length of, for example the car, would probably decrease the overall impacts for the car door panel, as the manufacturing and raw material extraction would be offset over a higher amount of years. This study shows that when considering a product with a long life length, the use phase is of most importance. This means that it is important to be accurate and precise when collecting data for this phase, signifying that the use of site-specific data is important. The impacts of the actual manufacturing process and sites are not as substantial for the overall impact, which means that average data for the manufacturing of components is an acceptable choice. If the environmental impact of the use phase depends on the weight of the product, it is important to consider information such as density differences. If there is a large density difference between the products/materials being investigated, a proper dimension of the reference flow would be volume rather than mass in order to take this into account in the use phase. Further methodological choices for the recyclable product with a short lifespan are that it is important to focus on collecting case-specific data for the manufacturing and recycling processes. Impacts from changing, for example, the electricity mix, are noticeable in the short lifespan case, which means that the location of the manufacturing site must be known. For the same case, it is also important to be accurate when choosing the end of life treatment. This leads to the question if the end-of-life treatment for biomass should be included in the life cycle for the bio-composite packaging. For the short lifespan product, the main impacts come from the manufacturing phase and the end of life treatment, which make the inclusion of both these phases important. Likewise, it is important to be able to compare the impacts from different end of life options, making the inclusion of the end of life treatment in the study critical.

Finally, it is important to keep in mind that for the polypropylene and polystyrene production, data were taken from the best available processes, while for the biopolymers, bio-polyethylene and polylactic acid, the technologies are not yet fully matured. This means that these results today show that it is preferable from an environmental point of view to use polypropylene, but in a couple of years, when the technologies have developed more, the results may be different, which means that a possible future scenario is that the impact of the differences in density could be offset by the manufacturing of the polymer, at least when comparing polypropylene and PLA.

8. Further Work

- To investigate the emissions connected to land use change and indirect land use change for the bio-based polymers. There may also be issues with food security in the countries where the raw material is cultivated, although to take this fully into account, further research is needed.
- To investigate on how a changed expected lifetime for a durable product will have effect on the overall life cycle impact
- To investigate how the quality of the material will be affected by the recycling process (i.e. if degraded or not). Another suggestion for further work regarding the recycling process is the investigation if it is possible to, instead of adding virgin polymer in the recycling process, add recycled polymer from discarded plastic products or a different polymer than the one already in the matrix.

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Appendix A.

Calculations

Functional unit: Long lifespan

The functional unit for the long lifespan product in this LCA study was set to one car door panel. The car door panel is assumed to have the dimensions 1m*0.5m*0.002m. The total volume of material needed for the manufacturing of one car door interior is then:

$$V = length * width * height = 1m * 0.5m * 0.002m = 1 * 10^{-3} m^3 \tag{A1}$$

The weight for a car door panel is calculated by:

$$m_{Car\ Door\ Panel} = \rho_{Material} * V_{Car\ Door\ Panel} \tag{A2}$$

The average density of polyethylene is 917.5 kg/m³ (UL ides n.d.), and the average density for polypropylene is 909 kg/m³ (Ineos 2010), leading to the assumption that density for pulp mix: bio-PE the same as for pulp mix: PP.

WPC is a bio-composite based on 50% wood flour (saw dust) and 50% polypropylene. The average density of dry wood flour is 520 g/dm³ (Clemons 2010). The density of the WPC is then calculated to:

$$\rho_{WPC} = 0.5 * \rho_{Wood\ flour} + 0.5 * \rho_{PP} = 0.5 * 520 \frac{g}{dm^3} + 0.5 * 909 \frac{g}{dm^3} = 715\ {}^{g}/_{dm^3} \tag{A3}$$

FPC is a bio-composite based on 40%pulp and 60% polypropylene. The density of dry pulp is assumed to be the same as for dry wood flour. The density of the FPC is then calculated to:

$$\rho_{FPC} = 0.4 * \rho_{pulp} + 0.6 * \rho_{PP} = 0.4 * 520 \frac{g}{dm^3} + 0.6 * 909 \frac{g}{dm^3} = 753.4\ {}^{g}/_{dm^3} \tag{A4}$$

Since the timeline for the functional unit is the same as the average life length of a car, which is 17 years (Jernkontoret 2003), the normalized mass of the functional unit (i.e. the reference flow) one car door panel:

$$Functional\ unit = \frac{weight\ of\ one\ car\ door\ interior}{Lifelength} \tag{A5}$$

Table A1: Density of the materials used for the manufacturing of the car door panel.

Functional Unit (kg) CAR DOOR PANEL	Density g/dm³
DuraPulp: PLA/ PLA-REC	755
Pulp mix: PP	630
Pulp mix: bio-PE	630
Compression moulding pure PP	909
WPC	715
FPC	753

Table A2: Weight of functional units manufactured using compression moulding.

Functional Unit (kg) CAR DOOR PANEL	Normalized Reference Flow (kg/year)
DuraPulp: PLA/ PLA-REC	0.044
Pulp mix: PP	0.037
Pulp mix: bio-PE	0.037
Compression moulding pure PP	0.053
WPC	0.042
FPC	0.044

Fuel Savings due to Choice of Material

The process transport, passenger car, is chosen to reflect the emissions from the use phase. The unit for this process is person*km. 1 person is assumed to weight 70 kg.

$$Relative\ Weight = \frac{Weight\ of\ car\ door\ panel\ (normalized\ to\ lifelength)}{Weight\ of\ one\ person} \tag{A6}$$

Table A3: weights of functional units (packaging relative 1 person).

Functional Unit (kg) CAR DOOR PANEL	Relative Weight of Functional Unit (kg/weight of 1 person)
DuraPulp: PLA/ PLA-REC	$6.2857 \ldots * 10^{-4}$
Pulp mix: PP	$5.2857 \ldots * 10^{-4}$
Pulp mix: bio-PE	$5.2857 \ldots * 10^{-4}$
PP	$7.5714 \ldots * 10^{-4}$
WPC	$6 * 10^{-4}$
FPC	$6.2857 \ldots * 10^{-4}$

In 2011, the average car in Sweden was driven 1218 *10 km (12180 km) (SCB 2012).

$$Relative\ Distance\ Car\ Door\ Panel\ = relative\ weight * distance \tag{A7}$$

Table A4: Relative distance for 1 car door panel per year.

Functional Unit (kg) CAR DOOR PANEL	**(kg/year)*year/(person)**
DuraPulp: PLA/ PLA-REC	7.656
Pulp mix: PP	6.438
Pulp mix: bio-PE	6.438
PP	9.222
WPC	7.308
FPC	7.656

Functional unit: Short lifespan

The functional unit for the short lifespan is assumed to be a packaging unit in the form of a tray. Generally, one DuraPulp: PLA packaging weighs 20 gram. This means that the volume for the packaging unit is:

(A8)

$$V_{Packaging\ Unit} = \frac{m_{Packaging\ Unit}}{\rho_{DuraPulp:PLA}} = \frac{20\ g}{755\ \ g/dm^3} = 0.02649\ dm^3 = 2.649 * 10^{-5} m^3$$

The weights of the functional units are then calculated using equation A9:

(A9)

$$m_{Packaging\ Unit} = \rho_{Material} * V_{Packaging\ Unit}$$

Table A5: Densities of the materials used for manufacturing the packaging unit.

Functional Unit (kg) Packaging Unit	**Density g/dm³**
DuraPulp: PLA/ PLA-REC	755
Pulp mix: PP	630
Pulp mix: bio-PE	630
Compression moulding pure PP	909
Polystyrene (assumed)	755

The lifespan is assumed to be 1 month to which the weight of the reference flow is normalized:

(A10)

$$Functional\ unit = \frac{weight\ of\ one\ packaing\ unit}{Lifelength} = \frac{Weight\ of\ one\ packaging\ unit}{\frac{1}{12} years}$$

Table A6: weights of functional units (packaging).

Functional Unit (kg) PACKAGING UNIT	**Normalized Weight of Reference Flow (kg/year)**
DuraPulp PLA/ DuraPulp PLA-REC	0.24
Pulp mix: PP	0.20
Pulp mix: bio-PE	0.20
Injection moulded pure PP	0.29
Injection moulded PS	0.24

Distances and Transportation of Polymers:

Transportation of PLA:
The transportation of PLA is assumed to be between Gothenburg and Nebraska. The distance between these two places is about 7300 kilometres (Evi n.d.). The traveling distance between Omaha, Nebraska and New York, New York is assumed to be equivalent to the distance from the PLA-Nature Works plant to the coast, which will be 2200 kilometres (City Distance Calculator n.d) . This is assumed to be by freight, rail. This means that the distance from the coast of the US to Gothenburg is:

(A11)

$$Distance\ over\ sea = Distance_{Omaha-Gothenburg} - Distance_{Omaha-New\ York} 7300\ km - 2200\ km = 5100\ km$$

This is assumed to be transported using transoceanic tanker.

Transportation of Polypropylene
The transportation of polypropylene and polystyrene is assumed to be produced in Germany; this means that the distance between Gothenburg and Berlin will be used. The means of transportation is assumed to be by train. The distance between Gothenburg and Berlin (by car) is about 740 km (Beräkna Avstånd, n.d.), the transportation means is assumed to be freight, rail. The same distance and means of transporting is assumed for the polystyrene.

Transportation of bio-PE
The distance from Sweden to Brazil is approximately 10500 km (Distance From To n.d.) The bio-polyethylene is assumed to be transported by transoceanic tanker.

How a changed polymer fraction has effect on the impact for long lifespan use

$$\rho_{PLA} = 1240 \frac{g}{dm^3}$$

(Henton et. Al 2005)

$$\rho_{PP} = 909 \frac{g}{dm^3}$$

(Ineos 2010)

It is assumed the density of PLA is not affected of the DuraPulp manufacturing process.

(A12)

$$m_{Car\ Door\ Panel} = V_{Car\ Door\ Panel} * (0.3 * \rho_{polymer} + 0.7 * \rho_{pulp})$$

$$\rho_{Durapulp:PLA} = 755 \frac{g}{dm^3}$$

(A13)

$$755\, {}^{g}\!/_{dm^3} = 1dm^3 * (0.3 * 1240 \frac{g}{dm^3} + 0.7 * \rho_{pulp})$$

(A14)

$$\rho_{pulp} = \frac{(755 - 1240 * 0.3\,)g}{0.7 * 1dm^3} = 547\, {}^{g}\!/_{dm^3}$$

Thereafter: the different densities for DuraPulp with the polymer fraction as a variable can be calculated by using the equation:

(A15)

$$\rho_{Pulp\ Varying} = \%_{Polymer} * \rho_{Polymer} + \%_{Pulp} * \rho_{Pulp}$$

Table A7: How the density of DuraPulp: PLA changes with a changing polymer fraction.

Percentage Polymer PLA	Density g/dm^3
70	1031
60	963
50	894
40	824
30	755
20	686
10	616

Recycling of packaging product

The yield in the recycling processes is assumed to be 90%. For a 50% collection rate, the amount of polymer that needs to be added in the recycling process to go from 70% pulp and 30% polymer to 60% polymer and 40% pulp is per kg of recycled product, this means that:

(A16)

$$\frac{60}{100} = \frac{x + 0.5kg * 0.3}{0.5kg + x} \rightarrow 0.6(0.5 + x) = x + 0.15 \rightarrow x = 0.3754\ kg$$

0.3754 kg of polymer needs to be in order to reach the required composition. This means that the flow of material from the recycling process is 0.87543 kg
(0.35 kg pulp + 0.52543 kg polymer, from the input of 0.5 kg of material with the primary composition and the addition of polymer)

(A17)

$$\frac{0.3754\ kg\ polymer}{0.87543\ kg\ material} = 0.42857\ kg \frac{polymer}{kg\ recycled\ material}$$

The amount of polymer needed per kg virgin material is then:

(A18)

$$\frac{kg\ polymer}{kg\ virgin\ material\ input\ in\ recycling\ process} = \frac{Yield_{recycling\ process} * Recycling\ rate * mass_{virgin\ material\ input\ in\ recycling\ process}}{kg\ virgin\ material} * \frac{kg\ polymer}{kg\ recycled\ material}$$

This means that for 50% collection rate:

(A19)

$$\frac{kg\ polymer}{kg\ virgin\ material} = \frac{0.428\ kg\ polymer}{kg\ recycled\ material} * \frac{0.9 * 0.50 * 1\ kg\ recycled\ material}{kg\ virgin\ material} = \frac{0.1926\ kg\ polymer}{kg\ virgin\ material}$$

Table A8: Amount of polymer needs to be added in the recycling process.

Collection Rate	kg polymer added per kg primary product
50% recycling	0.1926
100% recycling	0.38

Allocation Factors

Number of times the material can be recycled (equation adapted from ISO14041, 2000):

(A20)

$$N = 1 + Recycling\ Rate[yield + yield * \left(\frac{1}{1-(yield * Recycling\ rate)}\right)]$$

(A21)

$$N = 1 + 0.5\left[0.9 + 0.9 * \left(\frac{1}{1-(0.9 * 0.43)}\right)\right] = 2.27$$

For the primary product system:

(A22)

$$(1 - Recycling\ rate) + \left(\frac{Recycling\ rate}{N}\right) = (1-0.5) + \left(\frac{0.5}{2.27}\right) = 0.72$$

For the secondary product system:

(A23)

$$Recycling\ rate * \frac{N-1}{N} = 0.5 * \frac{2.27-1}{2.27} = 0.28$$

Table A9: Allocation factors and number of uses for the short lifespan product. Number of times the material can be recycled (equation adapted from ISO14041, 2000).

	50% recycling	100% recycling
Number of uses	2.268	10.9
Allocation factor: primary	0.72	0.09
Allocation factor secondary	0.28	0.91

Waste Composition for Recycling Case

The waste composition is calculated by the assumptions the waste (i.e. not recycled material) goes to incineration containing 30% polymer and 70% pulp, and that this amount depends on the collection rate. The recycled material goes to incineration containing 60% polymer and 40% pulp. The incineration of pulp is assumed to be equivalent with the incineration of packaging cardboard found in the ecoinvent database.

This means that:

$$Amount\ of\ pulp\ to\ incineration = weight_{functional\ unit} * (Recycling\ rate * 0.7 + (1 - recycling\ rate) * 0.4)kg \tag{A24}$$

$$Amount\ of\ polymer\ to\ incineration = weight_{functional\ unit} * (Recycling\ rate * 0.3 + (1 - recycling\ rate) * 0.6)kg \tag{A25}$$

Table A10: Masses going to incineration for DuraPulp: PLA and DuraPulp: PLA-REC for the unit of packaging.

PLA and PLA-REC	kg of pulp to incineration	kg of polymer to incineration
50 % recycling	0.132	0.108
100% recycling	0.096	0.144

Table A11: Masses going to incineration for pulp mix: PP and pulp mix: bio-PE for the unit of packaging.

PP and bio-PE	kg of pulp to incineration	kg of polymer to incineration
50 % recycling	0.011	0.09
100% recycling	0.08	0.12

Calculations of Environmental Impacts

The impact for the car door panel's lifecycle has been calculated using the formula:

$$Weight_{Functional\ Unit} * \left(\frac{impact\ for\ manufacturing}{kg\ manufactured\ material} + \frac{Impact\ for\ waste\ management}{kg\ material} + \frac{impact\ usephase}{person * km} * km * allocated\ weight\ of\ 1\ person\right) \tag{A26}$$

The impact for the packaging units lifecycle has been calculated using the formula:

(A27)

$$Weight_{Functional\ Unit} * \left(\frac{impact\ for\ manufacturing}{kg\ manufactured\ material} + * \frac{Impact\ for\ waste\ management}{kg\ material} + \frac{impact\ possible\ recycling}{kg\ recycled\ material}\right)$$

Inventory Data

Table A12 shows the specific inventory data for the Södra pulp manufacturing process. The pulp inventory data is the reported average total yearly use of resources for 2012 at the Värö plant.

Table A12: Inventory data for the Södra pulping process per tonne manufactured pulp of 2012 (Södra 2013)

INPUTS	
Raw Materials	
Wood (m^3 sub)	203800
Chemicals, oils etc. (tonnes)	70900
Water (Mm^3)	35
Other raw materials (tonnes)	988
External Energy	
Fossil fuel (MWh)…	31200
…of which fuel oil (m^3)	2540
Purchased biofuel (MWh)	241000
Purchased electricity (MWh)	22960
OUTPUTS	
Products/By-Products	
Pulp (ADt)	419000
Tall oil (tonnes)	9620
Turpentine (tonnes)	365
Ash (tonnes)	1100
Lime sludge (tonnes)	60200
Reject pulp (tonnes)	
Thermal energy (MWh)	245000
Biofuel (MWh)	233000
Electricity (MWh)	97700
Air emissions	
Gaseous sulphur as SO_2 (tonnes)	150
NO_x as NO_2	518
Dust (tonnes)	102
CO_2-fossil (tonnes)	10600
CO_2-biogenic (tonnes)	1015000
Water emissions	
AOX (tonnes)	0

COD (tonnes)	6850
TOC (tonnes)	2540
BOD_7 (tonnes)	658
TSS (tonnes)	743
SS 70 (tonnes)	195
N_{tot} (tonnes)	122
P_{tot} (tonnes)	8
Waste	
Deposited waste (BD tonnes)	1020
Hazardous waste (tonnes)	519

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Appendix B.

Life Cycle for DuraPulp: PLA/PLA-REC Car Door Panel

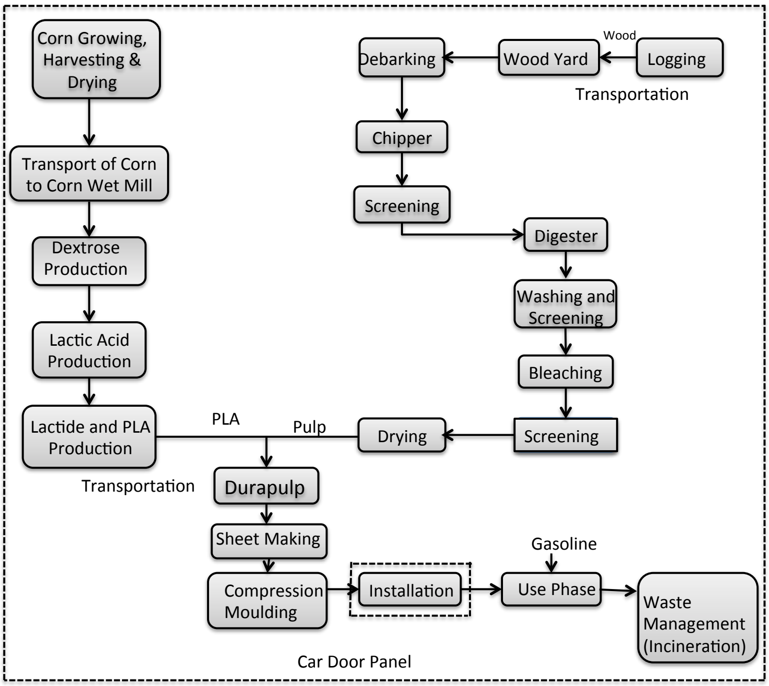

Figure B1: Life cycle for the compression moulding bio-composite manufacturing method where the polymer PLA and the fibre is pulp (DuraPulp: PLA/PLA-REC).

Life Cycle for Pulp Mix: bio-PE Car Door Panel

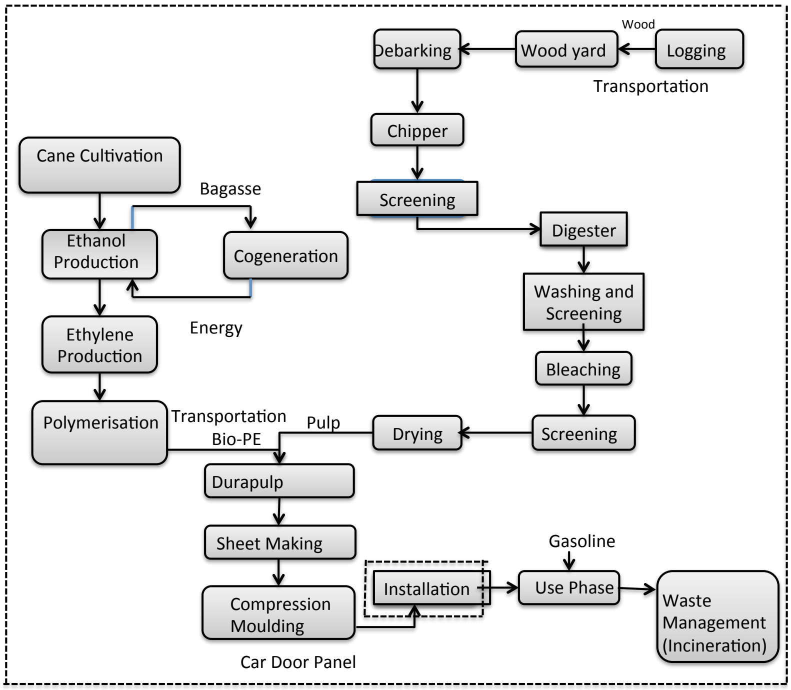

Figure B2: Life cycle for the bio-composite based car door panel using compression moulding and bio-P (pulp mix: bio-PE).

Life Cycle for Pulp Mix: PP Car Door Panel

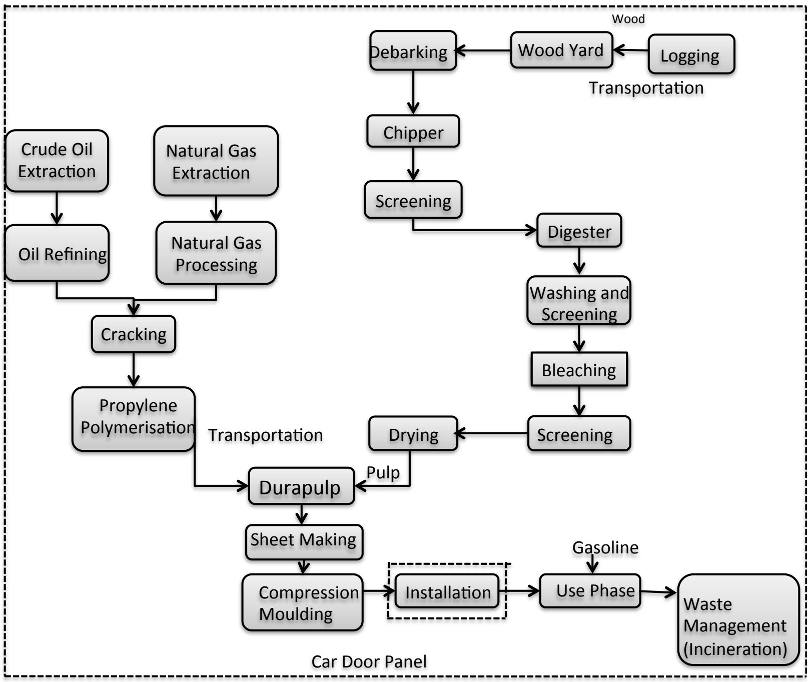

Figure B3: Life cycle for a bio-composite based car door panel using the manufacturing method compression moulding and polypropylene (pulp mix: PP).

Life Cycle for Pure PP Car Door Panel

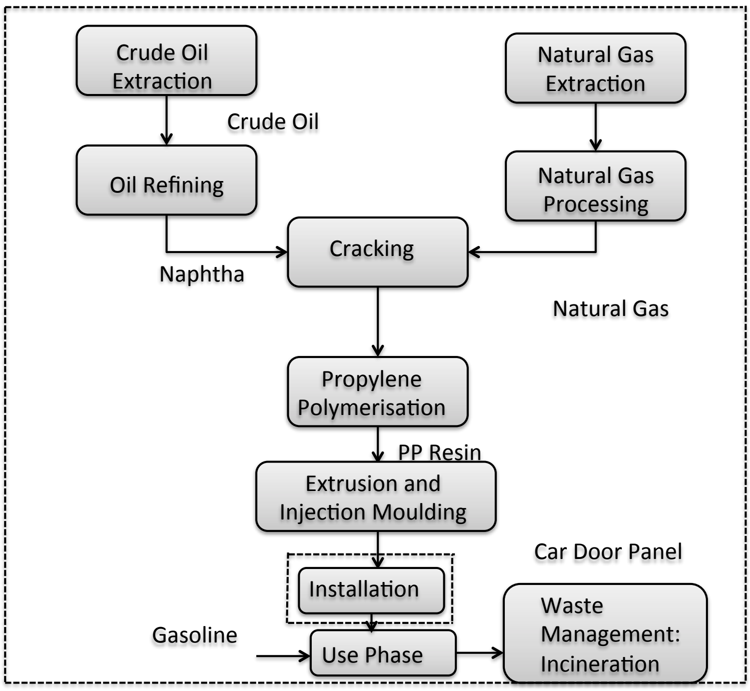

Figure B4: Life cycle for a car door panel based on pure PP.

Life Cycle for WPC Car Door Panel

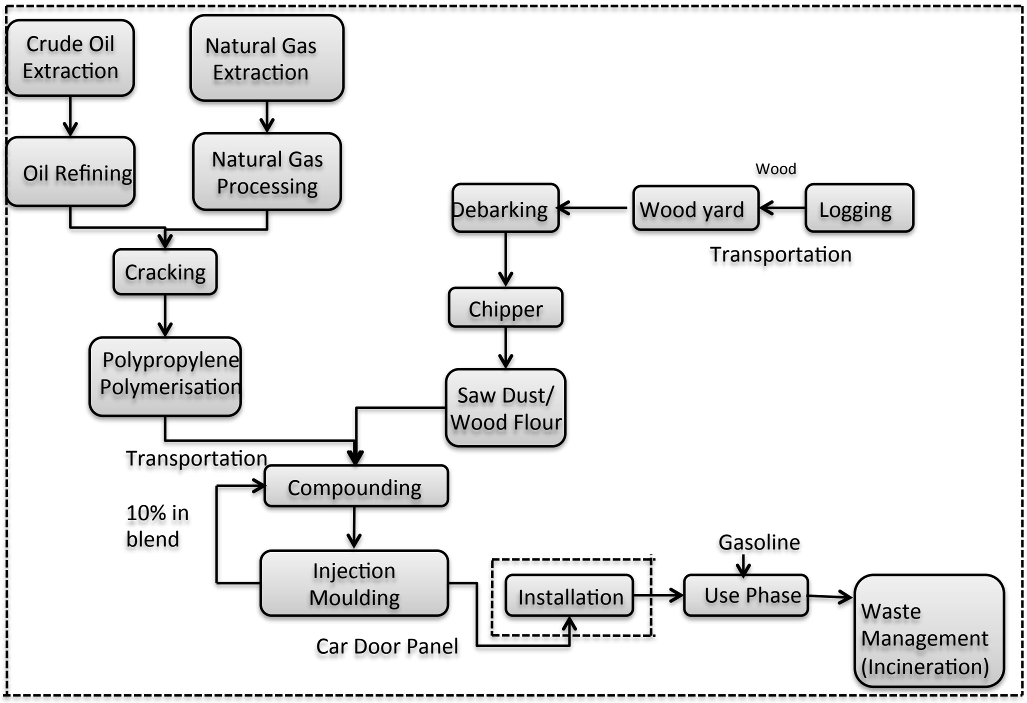

Figure B5: Life cycle for a bio-composite based car door panel based on wood flour and polypropylene (WPC).

Life Cycle for FPC Car Door Panel

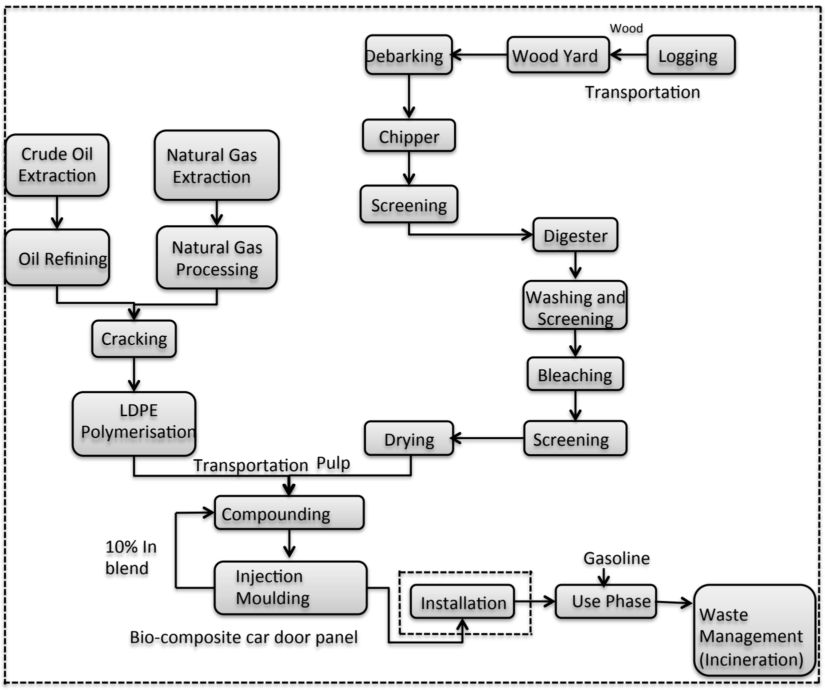

Figure B6: Life cycle for a bio-composite based car door panel using the manufacturing method injection moulding and polypropylene (FPC).

Appendix C.

Life Cycle for DuraPulp: PLA/PLA-REC Packaging Unit

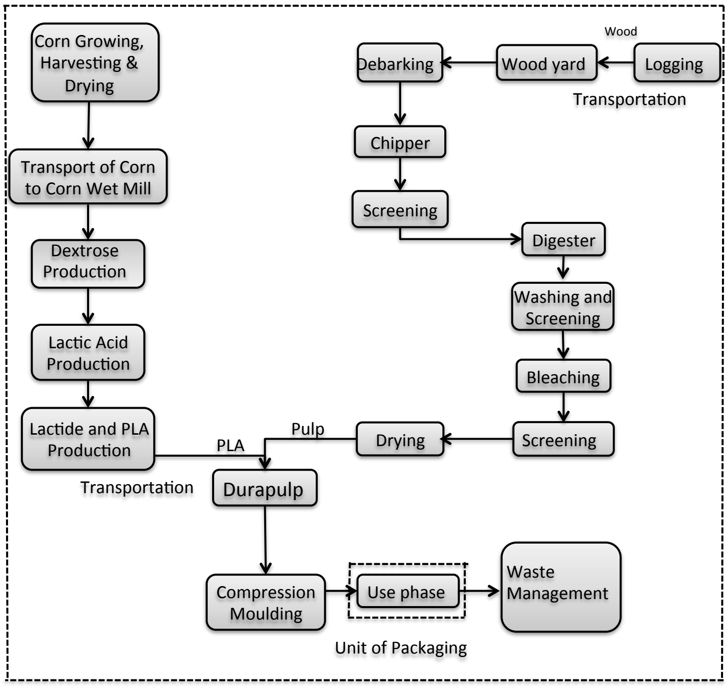

Figure C1: The lifecycle of the unit of packaging unit based on DuraPulp: PLA and DuraPulp: PLA-REC.

Life Cycle for Pulp Mix: bio-PE Packaging Unit

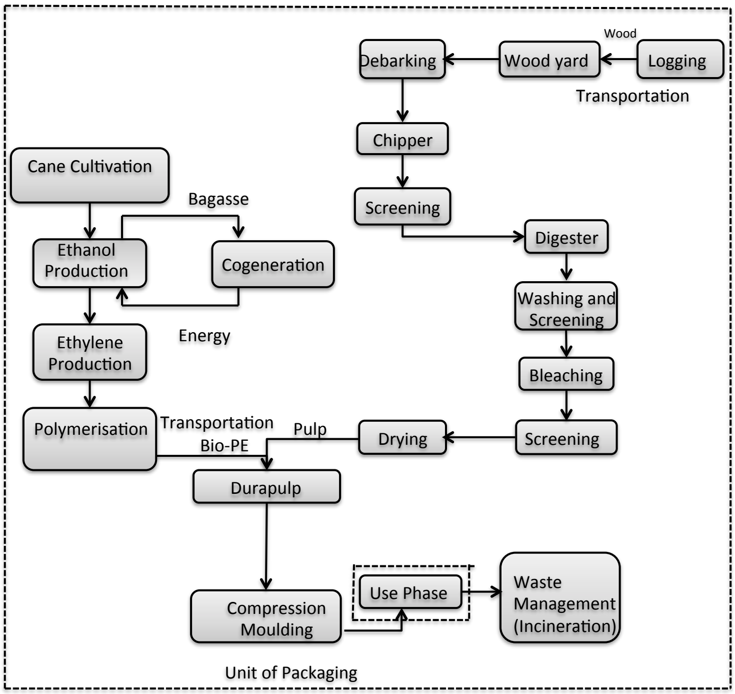

Figure C2: The lifecycle of the unit of packaging unit based on pulp mix: bio-PE.

Life Cycle for Pulp mix: PP Packaging Unit

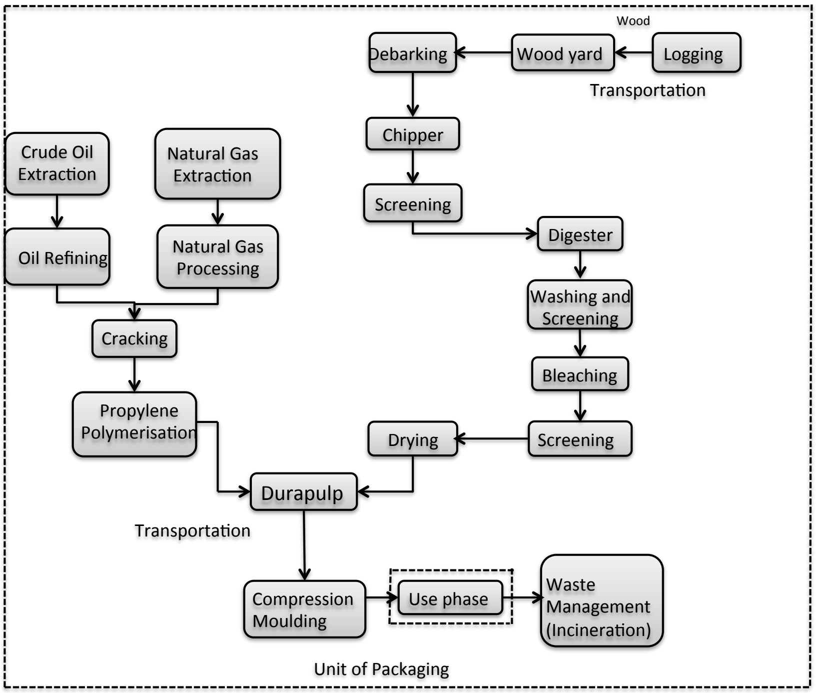

Figure C3: The lifecycle of the packaging unit based on pulp mix: PP.

Life Cycle for Pure PP Packaging Unit

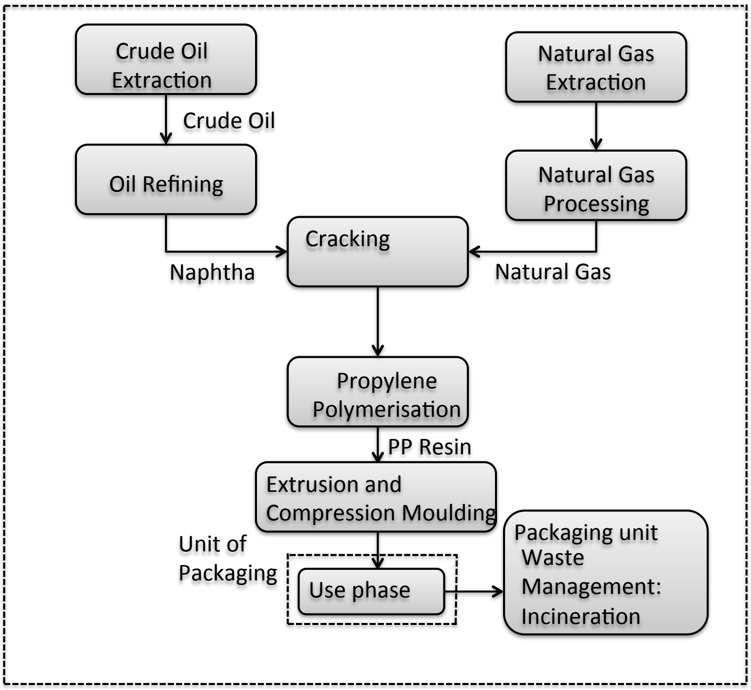

Figure C4: The lifecycle of the packaging unit based on pure PP.

Life Cycle for PS Packaging Unit

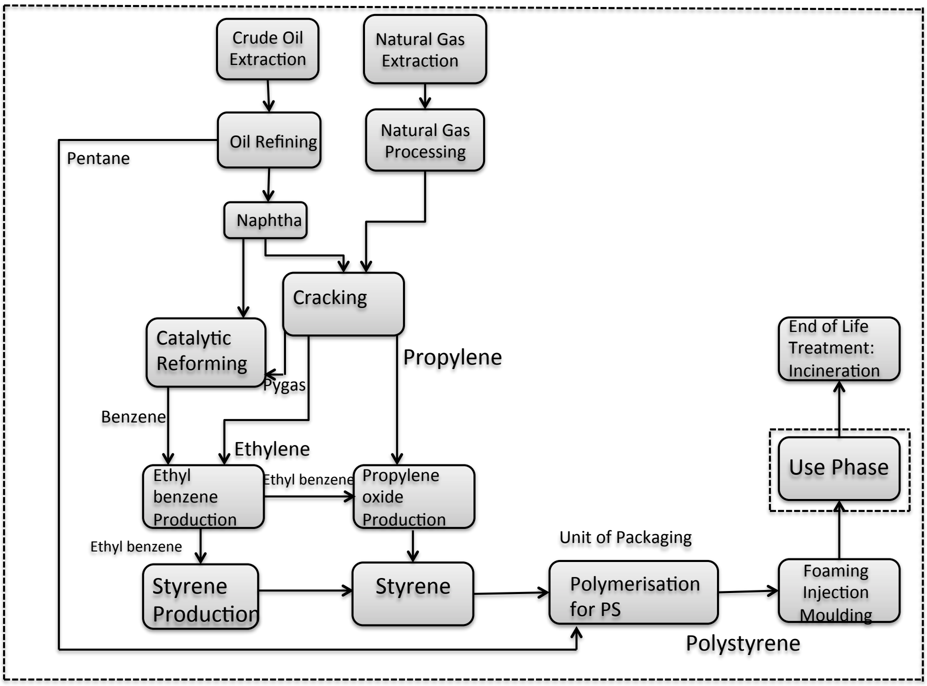

Figure C5: The lifecycle of the packaging unit based on expandable polystyrene.