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Comparative LCA of street sandboxes made of polyethylene and glass fibre reinforced plastic

Master thesis in Industrial Ecology

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Cover:
Street sandboxes made of polyethylene (left) and glass fibre composite (right).

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Abstract

Polyethylene and polyester are two very different types of plastics, both in material composition and qualities, but also in how it is produced and how it can be managed as waste. To be able to see these differences and assess the different impact on the environment the respective materials have, a life cycle assessment (LCA) is a preferable tool to use. In an LCA, all the different processes and flows are addressed, from the production of raw material to the waste management. In this study, two street sandboxes made of polyethylene (PE) and glass fibre reinforced plastic (GFRP) are assessed to be able to determine which box that has the highest impact on four different impact categories, and to see where these impacts originates from. The impacts studied are climate change, stratospheric ozone depletion, acidification and human toxicity. The study is a comparative, attributional LCA, with a cradle-to-grave perspective. Three scenarios are modelled, depending on different waste managements. Which management methods that are used depend on the waste management available for the respective materials.

The results show that for the base scenario, the GFRP-box has more than 50% higher impact on all impact categories compared to the PE-box. The biggest difference is found for human toxicity and stratospheric ozone depletion, with an impact difference of more than 80%. For the GFRP-box, the emissions contributing to the impacts originates, for all impact categories, from the production of polyester resin, followed by smaller impacts from the production of glass fibre. For the PE-box, the origin of the emissions varies between the impact categories, where the production of PE-granulates contributes to high impact on climate change and acidification, the production of electricity has high impact on stratospheric ozone depletion and human toxicity, and the production of aluminium used in the PE-box production has a large impact on human toxicity.

A sensitivity analysis was made to address the two boxes different lifetimes, where the impact from the GFRP-box increased due to the lower lifetime of the box, making the differences in impact greater. From a lifecycle perspective, the PE-box is better in all aspects addressed, mostly due to the lower emissions from the production of raw material, the recycling possibilities and the longer lifetime.

Key words: Life cycle assessment, polyethylene, glass fibre reinforced plastic, cradle-to-grave, street sandbox

Sammanfattning

Polyeten och polyester är två olika typer av plaster, både när det kommer till sammansättning av material och kvalitet, samt hur de produceras och hur avfallshanteringen ser ut. För att kunna göra en bedömning av skillnaderna mellan dessa materials påverkan på miljön, är en livscykelanalys (LCA) är en bra metod att använda sig av. Alla olika processer och flöden, från produktionen av råvaran till avfallshanteringen, inkluderas i en LCA. Denna studie ser till två olika typer av gatusandlådor, en tillverkad i polyeten och den andra tillverkad i glasfiberkomposit. Syfte är att avgöra vilken av lådorna som har högst påverkan på de fyra miljöpåverkningskategorier inkluderade i denna studie, samt att avgöra var denna påverkan härstammar från. Miljöpåverkanskategorierna inkluderade är klimatförändringar, stratosfärisk ozonnedbrytning, försurning samt mänsklig toxicitet. Studien är en jämförande bokförings LCA med ett vagga-till-graven perspektiv. Tre scenarion modelleras där avfallshanteringen ligger till grund för dessa. Vilka metoder för avfallshantering som används beror på vilka metoder som finns tillgängliga kommersiellt för de olika materialen.

Resultaten visar att i basscenariot har glasfiberlådan över 50% högre påverkan på alla miljöpåverkanskategorier jämfört med polyetenlådan. Den största skillnaden ses för mänsklig toxicitet samt ozonnedbrytning där skillnaden mellan lådorna är över 80%. För glasfiberlådan kommer den största delen av utsläppen för alla miljöpåverkanskategorierna från tillverkningen av polyester, följt av mindre utsläpp från tillverkningen av glasfiber. För polyetenlådan varierar uppkomsten till utsläppen mellan de olika miljöpåverkanskategorierna. Tillverkningen av PE-granulaten bidrar till stor påverkan på klimatförändringar och försurning medans tillverkningen av elektricitet har en stor påverkan på ozonnedbrytning samt mänsklig toxicitet. Även tillverkningen av aluminium har stor påverkan på mänsklig toxicitet.

En känslighetsanalys utfördes för de båda lådorna med fokus på deras livstid. Resultatet visade att påverkan från glasfiberlådan ökade när livslängden på polyetenlådan ökade. Detta resulterade i en större skillnad mellan de båda lådorna i deras totala påverkan på miljökategorierna. Sett till hela livscykeln av lådorna är det tydligt att polyeten lådan är bättre för samtliga miljöpåvekanskategorier. Där de lägre utsläppen från produktionen av råvara, möjligheten till materialåtervinning samt den längre livslängden är de viktigaste faktorerna.

Nyckelord: livscykelanalys, polyeten, glasfiberkomposit, vagga-till-grav, gatusandlåda

Preface

This study is a master thesis in industrial ecology within the master program Environmental Science at University of Gothenburg. The project has been conducted at Chalmers University of Technology at the Division of Environmental System Analysis and mediated by Miljöbron.

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Last, I would like to give a big shout out to Alexander and Hanna. You have given me so much energy and inspiration, in laughter and in tears, I would not have made it out in one piece without you guys, so thanks!

Abbreviations

- CFC = chlorofluorocarbon
- CH_4 = methane
- CO_2 = carbon dioxide
- DCPD = Dicyclopentadiene
- GFRP = glass fibre reinforced plastic
- GHG = greenhouse gases
- GWP = global warming potential
- HAP = Hazardous Air Particles
- HDPE = high density polyethylene
- LCA = life cycle assessment
- LCI = life cycle inventory analysis
- LCIA = life cycle impact assessment
- LDPE = low density polyethylene
- NO_x = Nitrogen oxides
- ODS = Ozone Depletion Substance
- PE = polyethylene
- PM = Particulate Matter
- POCP = Photochemical Ozone Creation Potential
- POP = Persistent Organic Compounds
- VIP = Vacuum infusion process
- VOC =Volatile Organic Compounds

Content

1. Introduction

In today's society, the importance of sustainability and environment are becoming more and more clear. Producers get pressure to produce sustainable and environmental products at a low cost. One way of addressing these issues are to produce products that has a low environmental impact in the production phase, are locally produced, uses recycled material, have a long lifetime and are recyclable. However, sometimes it can be hard to know what type of environmental impacts that a product has, or how large that impact is. Therefore, a lifecycle assessment (LCA) is a preferable tool to use when an investigation of a products environmental impacts for the entire lifecycle wants to be done.

In Sweden, the winters can get long and cold, causing many different problems on the roads and pathways across the country. Snow and ice are being removed with different methods, but the issue of icy and slippery roads remain. Therefore, there are street sandboxes filled with sand and gravel placed on strategic places to make the maintenance of these issues easier. Usually, the boxes are placed on top of stairs, next to walking paths and alongside roads with steep and long hills. However, the usage of boxes has become less common due to better equipment on the ploughing machines and sand spreaders placed in front of the tires of trucks. The most common type of sandbox is one made of glass fibre composite, which has been used for a very long time. However, there are some downsides with this type of box. The material used is quite sensitive against impact and weather, and therefore the boxes needs to be replaced with quite short intervals. This issue has made the market of street sandboxes look a bit different, with boxes being produced with different materials, trying to eliminate these issues. Boxes made of wood has been developed, however the issue of decomposing and moisture penetrating the box making the sand and gravel freeze has been some of the problems seen instead. One of the latest boxes on the market is one made of polyethylene. It has been seen to be able to handle some impacts better than the glass fibre box, and does not have the issue with moisture penetration. Furthermore, it is said that the box can be recyclable since it is produced by a recyclable plastic. This brings up some other questions, not only if the polyethylene box is better from a user perspective, but more important, *"Which is the best alternative for the environment?* The production of these boxes looks probably very different and has therefore different impacts on the environment. Also, the lifetimes of the boxes could vary due to the difference in fragility and material. To be able to say if this type of sandbox is better than the traditional one, a life cycle assessment needs to be done on both boxes.

This study

In this study, a LCA for two street sandboxes will be made to evaluate witch one has the lowest environmental impact and with this, determine where the impacts are biggest, which gives the opportunity to be able to reduce the impact in those areas.

The company Västia, who produces these types of polyethylene boxes, has as goal to find out for which environmental aspects that a street sandbox made of polyethylene is better from an environmental point of view, compared with a box made of glass fibre composite. They would like to be able to tell their customers in five bullet points why a box made of polyethylene is better than one made of glass fibre composite, environmentally speaking.

2. Background

2.1 Polyethylene and glass fibre composite

2.1.1 Polyethylene

Polyethylene (PE) is a thermoplastic and a synthetic material used in many different types of plastics. It can vary from high density (HDPE, ca 0.940-0.965 g cm^{-3}) to low density (LDPE, < 0.930 g cm^{-3}). HDPE is used in for example containers for household chemicals and LDPE in plastic films (CIEC Promoting Science, 2014). The plastic is resistant against impacts such as climate and temperature differences. Furthermore, it does not pollute the ground water and can be produced from biological substances such as ethanol from sugar canes. Waste treatment can be either energy recycling (combustion) or material recycling (Emil Deiss KG, 2017). In the combustion, only water, CO_2 and heat is emitted if the combustion is complete (Senior scientist polymer processing at Swerea IVF M. Strååt, personal contact, March 14th, 2017). The thermoplastic melts at a certain temperature and can therefore be reused and reshaped into new plastics when it is cooled, this can be done many times over (Molded Fiber Glass Companies, 2017). Plastics that are standing outside for a long time get lower qualities the longer it is exposed. However, PE plastics are normally protected with UV-stabilizers and are therefore quite resistant (Group manager Textile, Plastic and Ceramics at Swerea IVF H. Oxfall, personal contact, March 15th, 2017). According to Henrik Oxfall at Swerea IVF, for a rotationally moulded plastic that has a turbidity of more than 1cm, the lifespan of it should be very long.

Polyethylene is produced through addition polymerization of ethene, naphtha and gas oil. LDPE is then produced by compression of ethene at very high pressure (1000-3000atm) and at a temperature of 420-570K (148-298°C). The ethene is then passed through a reactor, including an initiator, and the ethene melts. Last the ethene is pressed and cut into granulates (CIEC, 2014).

2.1.2 Glass fibre composite

Glass fibre is made mostly from silica (SiO_2) where the raw material is melted and pressed into fibres that are cooled and sizing is made as a coating to protect the material and make it easier to apply in future production of composites (Sjögren, 2010). Furthermore, the glass is shaped into fibres and some help chemicals are added. There can be a mixture of recycled glass and silica sand in the production, but it is unknown if recycled material is used in glass fibre composites (Stig, 2012). The most common glass fibre used as reinforcement in composites is E-glass (Molded Fiber Glass Companies, 2017).

Fibre reinforced plastic (FRP) are plastics that contains polymer material resin (matrix) that is reinforced with glass fibre (Skrifvars et al., 2013). The plastic is usually unsaturated polyester which is a thermoset plastic and an organic compound where the polymer chains are bound with cross bindings and can therefore not be melted or reshaped (Research Engineer at Swerea SICOMP M. Juntikka, personal contact, March 22nd, 2017; Fråne et al., 2012). The box investigated here is made of dicyclopentadiene polyester (DCPD) (Head of production at Glasfiberprodukter I Trehörningsjö AB, personal contact, March 28th, 2017). Glass fibre reinforced plastic (GFRP) are stiff, strong, light in weight and can easily be designed after different specific requirements. However, they do not have a good temperature resistance, are sensitive against impact and are hard to recycle (Sjögren, 2010).

The thermoset plastic resin (matrix) contains a chemical called styrene. Styrene is used in plastics to add flexibility and strength to the products. It is a manufactured chemical, but it can be found in small amounts in different fruits and nuts. Styrene has a short lifetime in the environment since it is rapidly dispersed from the soils, air and surface waters (Molded Fiber Glass Companies, 2013). Dicyclopentadiene (DCPD), the matrix used in the boxes investigated, contains around 35-38% styrene, which is quite low compared with other plastics (Keson, 2009).

2.1.3 Lifetime

The lifetime of the boxes is hard to determine. The lifetime value used here is a mean value calculated from multiple estimated lifetimes given by different sources for the different materials. As seen in table 1, the estimated values given varies greatly, this due to the fact that the lifetime depends greatly on where the box is located and how it's being used.

Table 1. Estimated lifetime of the two boxes from multiple sources. A mean value is calculated from the values and rounded up.

Source	Polyethylene box	Glass fibre composite box
1	26	8
2	30	10
3	30	11
4	35	20
5	100	25
6		40
Mean	44,2	19

In the LCIA, the mean values have been rounded up to 45 and 20 years, this to make it easier to calculate on and compare the two. A sensitivity analysis is later made to look at the impacts from the boxes for the same amount of years, since the lifetime has a large impact on the emissions from the boxes. A box with a longer lifetime has a lower material requirement over time and therefore the emissions becomes lower. For the results of the different waste scenarios, the lifetime is not taken into consideration.

2.1.4 Facts about street sandboxes and earlier studies

Street sandboxes are today used to store gravel and sand, mainly for the usage in winter time when the roads, pathways and stairs are icy and slippery. The boxes are often placed on strategical places to make the maintenance easier. The most common type of street sandbox is one made of glass fibre composite, however the usage of polyethylene boxes has become more and more common. According to Stockholm Stad and Trafikverket, street sandboxes are becoming less common, mostly next to roads with steep hills, this due to that trucks have gotten better equipped with sand spreaders in front of their tires and that most people who drives has a mobile phone and can call for help if they get stuck on a slippery hill. Another reason for less street sandboxes out in the cities are due to that the people who perform maintenance has gravel and sand with them when they attend to the slippery roads and therefore the number of boxes being used are becoming less. However, there are still many street sandboxes used in for example schools, apartment complex and residential areas.

There are not many earlier studies made on street sandboxes, no LCA's has been found, making the gaps many, but at the same time so are the possibilities. Some studies regarding operations and maintenance of winter roads have been conducted, for example does Shi (2009) talk about the importance of optimizing winter maintenance with better planning and allocation of the resources used, to minimize wear and tear of the products and to place them at strategic locations. He does not address sandboxes directly, instead he addresses the general issues seen for winter maintenance today and how to make it more cost effective and sustainable. To place the box exactly where it is needed and in places where the wear and tear is minimized, the boxes could have a longer lifetime and less boxes would be needed. Other studies on winter maintenance can be found, however there is no mention of street sandboxes, most studies' focus lies in the type of chemicals and type of machines used. Therefore, there is a large gap in the studies available for this specific part of the winter maintenance sustainability. LCA studies on similar type of materials as this study has been conducted in several studies, but never has the materials been directly compared with each other. This study area is very narrow, and the demand is quite low, which makes the gaps many and the requests for further studies small. However, the environmental impacts cannot be disregarded, regardless of the demand, and therefore, this study is of importance for the future planning and sustainability work for the winter maintenance. Municipalities, authorities on infrastructure and other larger businesses will have interests in this type of study to optimize their work on sustainability.

Since there seem to be no specific requirements on sustainability when, for example, municipalities purchase street sandboxes, the difference in environmental impacts between different sandboxes are disregarded since they today are relatively unknown. Therefore is this study of high importance, to provide the municipalities and other users the necessary information needed to make a well though through decision on what type of street sandbox to use. Furthermore, to be able to see exactly where the largest impacts comes from for the boxes, both producers and users can make decisions accordingly.

3. Aim and objective

The aim of this study is to investigate two street sandboxes made of different material and by different processes, with focus on their individual environmental impacts. This is done using the LCA methodology.

The boxes have different waste management possibilities and therefore different waste management scenarios will be investigated. The dominant steps of the lifecycle, where the largest impacts can be seen, will be identified in a dominance analysis and suggestions on improvement for these steps will be conducted. It will be a comparative, attributional, LCA with cradle-to-grave perspective

The LCI is made on both boxes separately, each with the volume of 500 litres, but with different material composition and therefore different weight and inputs and outputs. The lifetime of the two boxes are different, however, this is not addressed in the LCI directly since the emissions assessed are done on one box of a certain volume, where the time is not included. Instead a sensitivity analysis is conducted in the LICA to address these differences and their impact on the overall impacts from the boxes.

Question

Which is the best alternative for the environment, a street sandbox made of polyethylene or one made of glass fibre reinforced plastic? Which of the different processes in the products lifetime has the highest impacts?

4. Method

The LCA will be a comparative, attributional LCA with cradle-to-grave perspective. Three different scenarios are modelled, based on different waste treatments. The different lifetimes of the boxes are addressed in a sensitivity analysis and the processes with the largest impacts are addressed in a dominance analysis. A system expansion is done to look upon the possible savings made by producing energy from the waste instead of using other energy sources.

4.1 LCA methodology

When talking about LCA, the phrase "cradle-to-grave" usually comes up. It means that the products whole life, from the raw material extractions (cradle) to the disposal of the product (grave) an all the steps between these (e.g. production and use) (Baumann et al., 2004), is considered. There are four steps when conducting an LCA of a product;

1. **Goal and scope definition** - formulating targets and limitations together with specifications of product and purpose of the LCA. Functional unit and system boundaries will also be formulated (Baumann et al., 2004; SLU, 2016).
2. **Inventory analysis** - construction of the model together with calculations of produced emissions and used resources (Baumann et al., 2004). This is the part of the LCA where all the data is collected from different sources and databases.
3. **Impact assessment** – classification and characterisation of resources and emissions connection to environmental issues (Baumann et al., 2004). Here, the environmental consequences are described and divided into environmental aspects.
4. **Interpretation of the results** – the environmental impacts is interpreted in relation to the life cycle (Baumann et al., 2004). Conclusions are formulated.

All these steps are connected to each other in different ways. In figure 1, the different steps are displayed with their interactions and possible iterations with each other.

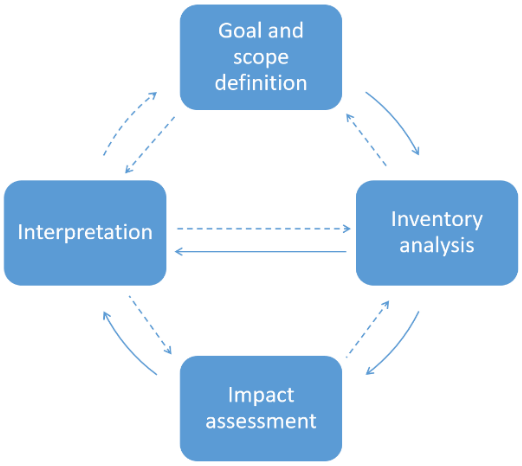


Figure 1. The four steps of the LCA procedure, and their interactions with each other. The four steps are put in the boxes, the arrows show in which order they are interacted and performed, broken arrows show possible iterations between the procedures (Baumann et al., 2004).

4.2 Scenarios description

For each box, there are 3 different scenarios modelled, all depending on the waste management. The first scenario, WS1, is modelled after how the waste management of the different materials are treated today. For the polyethylene box, it is 74% that goes to combustion and 26% that is material recycled. For the glass fibre reinforced plastic box, 85% goes to combustion and 15% is put on landfill.

Scenario number 2 and 3 are chosen to represent the extremes, where the treatment is either only combustion or only recycling/landfill. This to look upon how the different waste treatments emissions and therefor impacts differ, and with that be able to discuss which treatment that are better or worse from an environmental perspective. Scenario number 2, WS2, is calculated on that 100% of the waste goes to combustion. Scenario 3, WS3, is calculated on 100% material recycling for the PE-box and 100% landfill for the GFRP-box.

For the different scenarios, it is the amounts in input and output that changes. Where for WS2, the inputs and outputs connected to recycling and landfill are all put to zero, and only the inputs and outputs related to combustion are addresses. The same goes for WS3, but instead the inputs and outputs related to combustion are put to zero. For WS1, where both combustion and recycling/landfill is used, the values of the inputs and outputs connected to the waste management are adjusted after the percentage for each waste process, where the values for 100% combustion, recycling and landfill all stand as a reference. For more detail about the inputs and outputs, see table 2 and 3.

For all the scenarios, the lifetime of the PE-box is 45 years and for the GFRP-box it is 20 years.

5. Life cycle assessment

5.1 Goal and scope

The purpose of the LCA is to compare two street sandboxes of different materials. The boxes have different waste management possibilities and therefore different waste management scenarios will be investigated. The dominant steps of the lifecycle, where the largest impacts can be seen, will be identified in a dominance analysis and suggestions on improvement for these steps will be conducted.

It will be a comparative, attributional, LCA with cradle-to-grave perspective.

5.1.1 Scope and modelling requirements

Which options to model?

The product that will be investigated in this study is a street sandbox with the volume 500 litres. It will be a comparative investigation between a box made of polyethylene from the company Västia trough RotationsPlast and a box made of glass fibre composite, no specific company, but with information from several sources. The box made of polyethylene is rotationally moulded in a closed process. The box made of glass fibre reinforced plastic is a composite of glass fibre and polyester, made by vacuum infusion.

Functional unit

One box with the volume 500 litres.

Initial flow chart

Figure 2 shows the general flows that are present in the production of both type of street sandboxes. First, there are multiple of different raw materials going into the production of the boxes, together with some sort of energy. Transport of the materials are market with a “T” and are present in most processes. The production of the boxes looks different, which is further explain in the LCI, but the outcome is the same, one box. The box is transported to different users, which in this study are located in Gothenburg. When the box has been used, it is treated as waste and goes through different waste management processes depending on the material composition of the box.

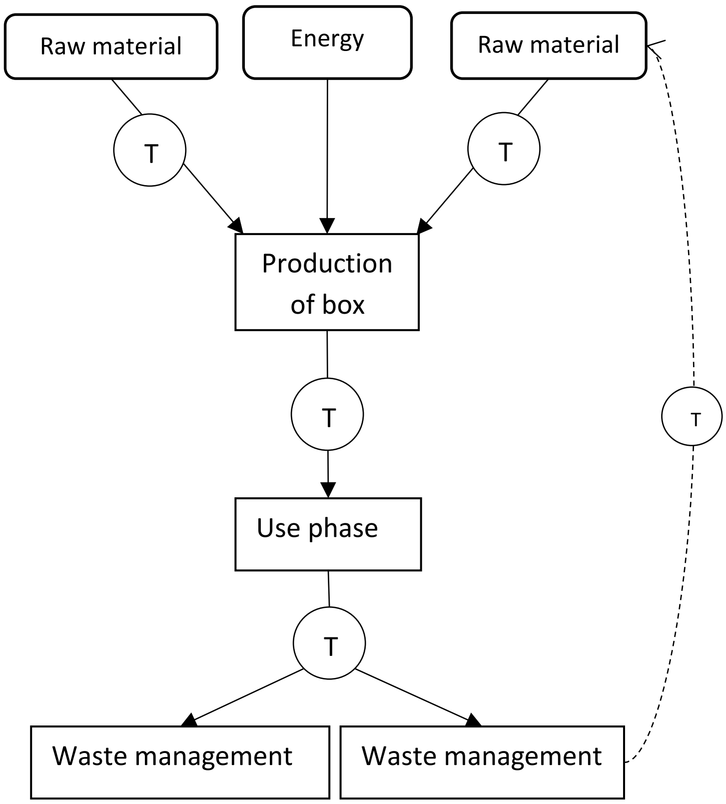


Figure 2. Initial flow chart for both sandboxes. The dashed line represents the recycling of material going back into the production of the box. Transport between the different processes are marked with a "T" inside a circle.

Choice of impact categories and method of impact assessment

According to ISO 14040, the environmental impact categories that should be included is; resource use, ecological consequences and human health. These are only headlines for the categories, they need to be divided into sub categories.

For this study, the environmental impacts to be considered will be;

- Climate change
- Stratospheric ozone depletion
- Acidification
- Human toxicity

Earlier study by AlMa'adeed et al. (2011) showed that production of virgin PE has an impact on the categories human toxicity, acidification (from emissions to air), global warming potential and abiotic depletion.

- *Climate change (global warming)*

The greenhouse effect is something that occurs naturally on earth and is the core of the earth's climate. It means that the greenhouse effect sustains the balance between incoming sunlight and outgoing heat, it sustains the energy balance with CO_2 and water vapor. However, due to the high emissions of greenhouse gases (GHG) such as CO_2 and CH_4, the greenhouse effect is larger than it should be naturally, which has led to a rapid heating of the earth, in other words; global warming. The warming of the earth makes the snow, ice and glaciers in the polar regions melt, making the darker ground exposed, leading to an even more rapidly heating due to a higher absorption to the darker ground (less heat is emitted back into the atmosphere). It becomes an evil spiral which makes the earth heat very rapidly (Rummukainen, 2005). This is a very important category when looking at environmental impacts, since it covers many different areas of a products lifecycle. In this LCA, the largest impacts on climate change will most likely come from burning of fossil fuel, for example combustion of waste, production of electricity and transport.

- *Stratospheric ozone depletion*

Ozone depletion is a degradation of the stratospheric ozone layer due to emissions of ODSs (ozone depletion substances) such as CFCs and bromine halons (Stig, 2012). ODS has a long atmospheric lifetime and the and reaches the stratosphere after some amount of time after they have been admitted. While in the stratosphere, CFCs are dissolved by UV-light and free chloride atoms are released to react with the ozone which leads to depletion (SMHI, 2016). Example of ODSs products are aerosols, halons in fire extinguishers and solvents (United Nations, n.y). In this study, the ODSs' will most likely come from the electricity production and transportation. This is strongly related to global warming potential (GWP), and will therefore be related to the climate change category. Furthermore, these substances affect human health and damages vegetation (Gontia, 2014).

- *Acidification*

Acidification means a change in acidity (either in soil or in water), a lower pH level due to higher concentrations of hydrogen ions (H^+), which is usually a consequence of deposition of inorganic substances like nitrates, sulphates and phosphates (mostly NO_x, NH_3 and SO_2) (Stig, 2012; Nationalencyklopedin AB, 2017). These substances are normally a result of acidic air pollutants from burning of fossil fuels and other materials, mostly from cars and ships (Nationalencyklopedin, 2017). When these compounds are added to the soil and water, the base cations are replaced, causing a decline in pH and the removal of many important plant nutrients. Furthermore, when the soil become acid, toxic ions of inorganic aluminium are dissolved into the water, causing negative effects on fish. Many of the acidic substances are transboundary pollutants which means that they can be distributed over a large area, sometimes they can be transported over oceans and land into other countries with air flows and be deposited as wet deposition or as dry deposition. (Pleijel, 2007).

The burning of material to produce energy will have impacts on acidification. This is strongly related to global warming potential (GWP), and will therefore be related to the climate change category.

- *Human toxicity*

There are many ways in how a product can have effects on human health. It can be through emission to air that are inhaled, through direct contact with skin, emissions to water that is drunken or in contact with the skin, emissions to soil that can affect plants that are eaten etc.

It will be of high importance to consider this category for the GFRP-box since products made of glass fibre can become porous and particles/dust will be released and end up in nature and in lungs and skin of humans. Mainly the particles of glass fibre are an issue in the production of glass fibre and the processing into glass fibre products, but it can also be an issue when the products break or is wearied out. If the glass fibre particles come in contact with the skin, irritations are commonly seen (dermatitis) and in contact with eyes, eye irritation is (OSHA, 2005). Furthermore, if the particles are inhaled, difficulty in breathing like asthma is commonly seen, and according to some research, it can lead to cancer as a consequence (OSHA, 2005; Stanton et al., 1977). When producing or processing glass fibre products, there is a large release of particles. This affects the working environment and can lead to health consequences for the workers. Therefore, human toxicity also needs to be considered in the production of GFRP-boxes, since the workers put themselves at risk for exposure of both glass fibre particles and solvent agent. However, these emissions will most likely be very small and therefore not give that much impact in the overall human toxicity.

Air pollutions of many kinds, for example CO, SO_2, NO_x, VOCs, O_3, heavy metals and particles, have different effects on human health since they all have many different properties. They can give effects such as heart disease, lung cancer and different levels of respiratory diseases. The level of effect from the emissions are related to long-term and short-term exposure (Kampa et al., 2007).

- *Impact assessment method*

Impact assessment method for this LCA will be CML. CML is a database used for LCIA (Life Cycle Impact Assessment) developed by the Institute of Environmental Sciences at University of Leiden, Netherlands. It contains characterisation factors for characterisation methods. This method is well recognised and all impact categories that will be address are included.

System boundaries

The LCA will have a cradle to grave approach. The cradle will be at the manufacturing of the street sandbox (the rotational moulding for PE and the vacuum infusion for the GFRP) and the grave will be at the waste management of the two materials, which means looking at the recycling, combustion and landfill.

- *Geographical boundaries*

The production of the polyethylene box is done in Sweden, in the city of Munka-Jungby. Since the LCA is made for the company that produces the PE-box, the location of production of the GFRP-box will be at the same location, to be able to make a proper comparison between the two boxes. The production of the raw material differs between the two, the polyethylene powder used for the PE-box is produces in Gravendeel, Holland and the aluminium hinges is produced in Gothenburg. For the GFRP-box, the origin of the raw material is more insecure since there are no specific producer of the box in this investigation. However, information collected from different sources show that the glass fibre and iron hinges used for the production is mostly purchased in Gothenburg. The polyester resin is produced in either Kallo, Belgium or in Terneuzen, Netherlands. Since the origin could vary, a mean value of the distance between the two cities and Munka-Jungby is made to be able to calculate on the transportation. The boxes are assumed to be sold and used in Gothenburg. For the waste management, the locations are for combustion; Renova’s waste-to-energy power plant Sävenäs located in Kviberg, just outside of Gothenburg city, for landfill; Renova’s landfill site “Tagene” at Hisings kärra and for the recycling; Swerec’s recycling station outside of Bredaryd.

- *Time horizon*

The two boxes are assumed to have a large variation in lifetime. There are no specific data on the lifetime of the two boxes, therefore the lifetime will be an estimate of different sources and statement from experts in the area. The conclusion of the PE-box lifetime is that it will have a very long lifetime, longer than the GFRP-box, since it does not break as easily from impact and does not degrade much from weather and UV-light. The GFRP box however, does not live as long since it breaks easily due to its fragility against temperature differences and impacts. For all the scenarios in the LCA, the lifetime for the PE-box will be 45 years and for the GFRP-box it will be 20 years. The difference in lifetime has been chosen not to be a part of the scenarios calculations, this to be able to only look at the impact of one box, regardless of its lifetime. A sensitivity analysis is later made to address the difference in lifetime, since the lifetime is assumed to have a large impact. For the production, use and waste management, data is collected from present time.

- *Production of capital goods*

Is not included in this LCA, only the inputs and outputs of the actual production is included. Environmental impacts related to personnel is also not included.

- *Cut-offs*

One cut-off lies within the production of raw-material. For this, data from the database *Ecoinvent* will be used, which will give an average of the impacts from the upstream processes. Mostly the data is specified to Europe, sometimes the world and for some cases specified to Sweden. Due to this, and due to that the interest lies in the production and waste management impacts, the main focus of the LCA will lie in the production phase and the downstream processes from that.

- *Other products’ life cycles and allocation*

Allocation is met in the waste management part, where especially landfill and incineration consists of many different products, and therefore it is hard to say exactly what effect the boxes gives. This will be addressed by looking at the specific emissions that the different materials give in each of the waste management types.
For this study, there will be a closed loop recycling of both the waste produced in the production of the box and in the waste of the actual box in its end of life. The recycling is only addressed for the PE-box.

- *Background and foreground system*

The foreground system of this study lies between the production of the boxes and the waste management. The background system is all other processes upstream of the processes in the foreground system (figure 3 & 5).

Principles for allocation & data quality requirements

Data for the production of the box made of PE will be collected from the production company RotationsPlast. Some data upstream the production of the box will be collected from

Ecoinvent. Data on emissions from transport will be connected with the data used from *Ecoinvent*, with data on quantity, type of vehicle and length of the transport from the production companies, Västia and other sources. Data for waste management is collected from different sources, mostly industry-specific. Other emissions from the processes are directly taken from *Ecoinvent* together with some data from different sources. All the data used can be seen in Appendix B and table 2 and 3, together with the different sources used.

For the glass fibre box, data will be collected in a similar way as for the PE-box, with data from both the database *Ecoinvent*, production specific data and from other sources. For the waste management and transport emissions, data will be used from different sources (some same as for the PE-box) and *Ecoinvent*.

All the data used has been collected from legit sources, either publications in large scientific journals, by authorities, from published books and by sources that has good knowledge in the area and are trust worthy. Some information and data has been collected personally from people in the business of producing the different boxes, from scientist at various locations and from other people that has good knowledge about the different processes and materials addressed.

5.1.2 Limitations and assumptions

For the glass fibre box, there are no recycled material used in the production. For the polyethylene box, the polyethylene powder used is mostly from virgin PE. The waste generated in the production is however sent to another location to be re-granulated, which is then sent back to the production to use again. Therefore, there is a closed-loop recycling of the produced waste in the production.

It is assumed that the recycled material produced from the recycling process of the wasted box is used again in the production of the box, making this a closed-loop recycling system. Another assumption is that the recycling process is 100% efficient, meaning that the same amount of plastic going into the recycling comes out as new PE-granulates to use again in the process.

For the transportation of material, product and waste, the same type of transport is used, this to make it easier to compare the different processes. The type of transportation used is a EURO 5 truck of 16-32 metric ton, used from *Ecoinvent* for Europe.

5.2 Inventory analysis (LCI)

Since the two boxes are made from different material and by different production methods, their inputs and outputs look quite different. In this chapter, the different input and outputs will be presented for each box individually, a more detailed flowchart for both boxes is presented, together with the health and environmental effects, followed by some details about the different waste managements for the materials.

5.2.1 Polyethylene box

Flowchart and inventory data

Figure 3 shows a flowchart for the polyethylene box. The upstream processes that are a part of the background process have rounded edges on the boxes. The flows of recycling materials are marked with dashed lines. All the transport between the different processes are marked with a "T" inside a round box (figure 3).

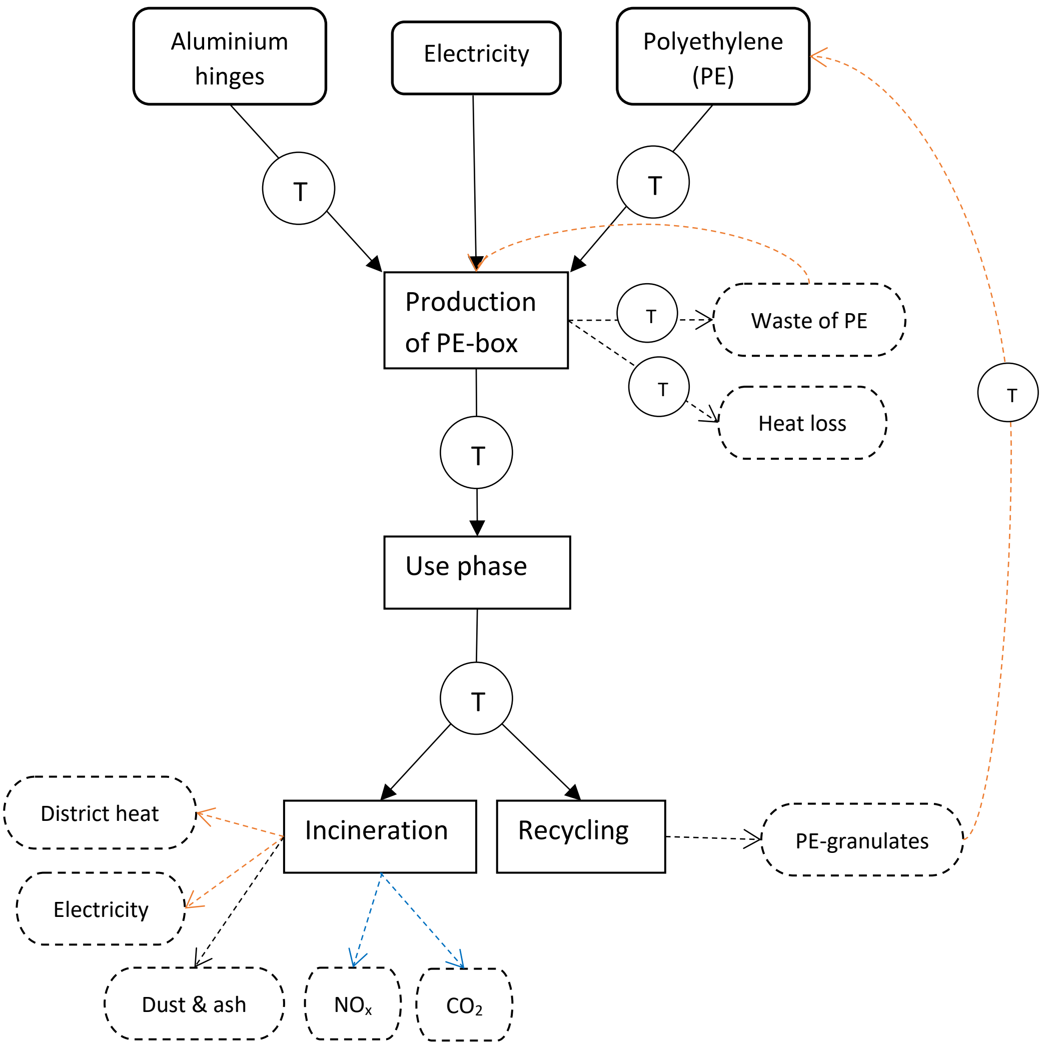


Figure 3. Flowchart for the PE-boxes lifecycle. The dashed lines are the outflows from the systems, where the orange lines are different kinds of recycling (both material and energy) and the blue lines are emissions to air. Transport between the different processes are marked with a "T" inside a circle.

Table 2 shows the inventory data collected for the PE-box, normalised per activity, which here is one box of 500l. The data shows all the inputs and outputs in the lifecycle. For more detailed data on how the emissions are calculated, see Appendix B. The data is divided into the different waste scenarios, where the first scenario, WS1, has 74% combustion and 26% recycling, WS2 has 100% combustion and WS3 has 100% recycling.

Table 2. Inventory data for the PE-box, normalised per activity (one box of 500litre), divided into the different scenarios.

	WS1	WS2	WS3
Production PE-box			
INPUT			
PE powder (kg/box)	17,39	23,5	0
Al hinges (kg/box)	0,12	0,16	0
Electricity (MJ/box)	234	234	234
Transport (kg*km)	29787	29787	29787
OUTPUT			
PE-box (kg/box)	23,66	23,66	23,66
Heat loss (MJ/box)	6,8	6,8	6,8
Use phase			
INPUT			
PE-box (kg/box)	23,66	23,66	23,66
Transport (kg*km)	4401	4401	4401
OUTPUT			
Waste PE-box (kg/box)	23,66	23,66	23,66
Waste management			
INPUT			
Waste PE-box (kg/box)	23,66	23,66	23,66
Transport (kg*km)	1922	137	7003
Electricity (MJ/box)[1]	0,45	-	1,72
OUTPUT			
District heating (MJ/box)	661	894	-
Electricity (MJ/box)	90	122	-
CO_2 (kg/box)	58	71	22
NO_x (kg/box)	0,04	0,05	-
Ash/unburned material (kg/box)	0,5	0,7	-
Dust (10^{-5} kg/box)	3	4	-
Aluminium dust (10^{-5} kg/box)	9	12	-
PE-granulates (kg/box)	6,1	-	23,5
Aluminium (kg/box)	0,04	-	0,16
CO (10^{-3} kg/box)	1,3	-	4,8
CH_4 (10^{-5} kg/box)	9,6	-	40
N_2O (10^{-4} kg/box)	3,6	-	14
HC (kg/box)	0,04	-	0,16

[1] Recycling plastic: Head of production Swerec, personal contact, May 18th, 2017.
Recycling aluminium: Damgaard et al. (2009)

Starting with the production of the box, the rotational moulding has no direct emissions other than heat from the oven and plastic waste that has a closed-loop-recycling, therefore this waste is not seen in the LCIA. The inputs in the production are raw material (PE-powder and Al-hinges) and large amounts of electricity. For most of the processes, there are transport of the inputs. Upstream processes of the production of the raw materials used and the energy used are a part of the background system and is therefore not addressed in this study. Data on the upstream processes are collected from the database *Ecoinvent*. As seen in table 2, the amount of input of raw material varies between the different waste scenarios, this due to the amount of recycled material going in instead. For example, the input of raw material is zero when the recycling rate is 100%, since all material going into the process is produced from recycling material that has originated from a used box.

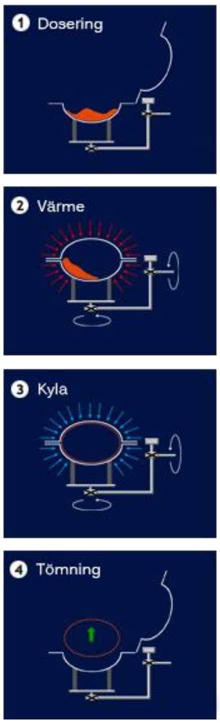
Looking at the use phase, there are no specific emissions, the input and output are the same, one box, since it is assumed that the box will stay relatively intact in the use phase.

The emissions from the waste scenarios are calculated for combustion from the materials heat and combustion values, the combustion plants emission values of NO_x and the materials CO_2 emission factor. How the emissions from the combustion and recycling is calculated is described in Appendix B. For recycling, there is polyethylene and aluminium as outputs since 100% of the material is recycled. Therefore, for WS3, the input of raw material is set to zero due to the closed-loop-recycling. For recycling, there are some amounts of electricity going into the process, whereas for the combustion, the usage of electricity and heat is not accounted for since the process generates both heat and electricity and the amounts used has therefore been subtracted from the produced amounts in the output. Also, the transport looks different for the waste scenarios, where the combustion plant is located in Gothenburg and the recycling facility is located outside of Bredaryd.

Production - rotational moulding

The polyethylene street sandbox investigated is made through rotational moulding. This process makes the product heat, cold and chemically resistant, gives it a long lifespan and it becomes tolerant against physical impacts and degradation (RotationsPlast, n.y.b).

Rotational moulding is a closed process where the LDPE powder only changes its state of aggregation, nothing chemical is involved and no substances are added. No recycled material is used in the process by RotationsPlast, it is only virgin LDPE that is used today. This due to the risk of getting contaminated PE from recycled materials. The small amounts of plastic waste produced in the process is sent for recycling where it is granulated to powder. The recycled waste is then sent back to RotationsPlast where it is used again for several types of rotationally moulded plastic products (Product Engineer at RotationsPlast M. Håkansson, personal contact, February 10th, 2017; Production manager at Västia Plastindustri AB A. Sülau, personal contact, February 28th, 2017). However, in this study, the waste produced in the production is assumed to be re-granulated and used again in the production of the box specifically, and not for other products.



In figure 4, the method for rotational moulding is described. The raw-material used is low density polyethylene (LDPE) in powder form, which has a medium stiffness and a density of 0,935 (A. Schulman, 2015). First (no. 1), the powder is put into a mould made of sheet material. Second (no. 2), the mould is put on a trolley which is then put in an oven and heated up in 300°C. After a few minutes, the tool starts to rotate around an axis, tilted back and forth, so the LDPE melts to liquid form and starts to paste to the walls. The liquid then starts to seep out and you get a polyethylene film on the tool itself. Third (no. 3), the trolley is taken from the oven and put into a cooling chamber, where fans blow cool air on the tool. Forth (no. 4), the mould is opened and the product can be taken out. The box is then processed, where it is cut open and hinges is put on (Product Engineer at RotationsPlast M. Håkansson, personal contact, February 10th, 2017).

Figure 4. Flow chart of the production of sandboxes made of rotationally modelled polyethylene. Translation; 1 = Dosage, 2 = Heating, 3 = Cooling, 4 = Emptying. (RotationsPlast, n.y.a).

There are only very small amounts of waste produced in the cleaning of the moulds. This waste is swept away or rubbed down mechanically and then thrown in combustible waste (Product Engineer at RotationsPlast M. Håkansson, personal contact, February 23rd, 2017). Since this waste is so small, it is disregarded in this study.

Waste management

The two most common waste treatment of polyethylene products are either combustion or material recycling. This due to the high energy value in the material and its recyclability (Group manager Textile, Plastic and Ceramics at Swerea IVF H. Oxfall, personal contact, March 15th, 2017). Today, 76% of the PE-plastics are combusted and 24% is material recycled.

5.2.2 Glass fibre reinforced plastic box

Figure 5 shows a flowchart for the glass fibre reinforced plastic (GFRP) box where the upstream processes that is a part of the background system has rounded edges on their boxes. All the transport between the different processes are marked with a “T” inside a round box and the dashed lines are outflows from the processes (figure 5).

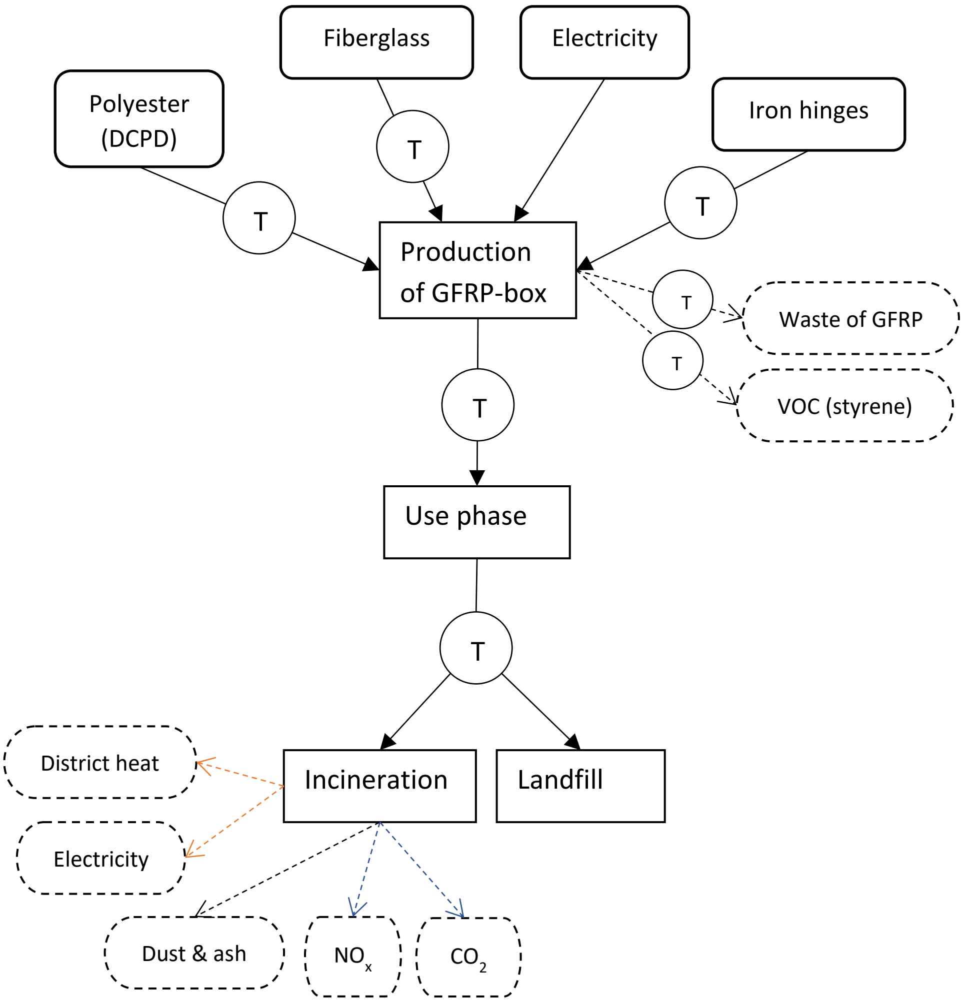


Figure 5. Flowchart for the lifecycle of a street sandbox made of glass fibre reinforced plastic. The dashed lines are the outflows from the systems, where the orange lines are energy recycling and the blue lines are emissions to air.

Table 3 shows the inventory data collected for the GFRP-box, normalised per activity, which here is one box of 500l. The data shows all the inputs and outputs in the lifecycle. For more detailed data on how the emissions are calculated, see Appendix B. The data is divided into the different waste scenarios, where the first scenario, WS1, has 85% combustion and 15% landfill, WS2 has 100% combustion an WS3 has 100% landfill.

Table 3. Inventory data for the GFRP-box normalised per activity (one box of 500 litres), divided into the different scenarios.

	WS1	WS2	WS3
Production GFRP-box			
INPUT			
Polyester resin (kg/box)	26,4	26,4	26,4
Glass fibre (kg/box)	7,1	7,1	7,1
Iron hinges (kg/box)	2	2	2
Electricity (MJ/box)[2]	69	69	69
Transport (kg*km)	29228	29228	29228
OUTPUT			
GFRP-box (kg/box)	35	35	35
Waste GFRP (kg/box)	0,5	0,5	0,5
Styrene (kg/box)[3]	0,09	0,09	0,09
Use phase			
INPUT			
GFRP-box (kg/box)	35	35	35
Transport (kg*km)	6510	6510	6510
OUTPUT			
Waste GFRP-box (kg/box)	35	35	35
Waste management			
INPUT			
Waste GFRP-box (kg/box)	35	35	35
Transport (kg*km)	219	203	312
Electricity (10^{-3} MJ/box)[4]	3,6	-	24
Diesel (10^{-3} l/box)[4]	4,3	-	29
OUTPUT			
District heating (MJ/box)	741	871	-
Electricity (MJ/box)	101	119	-
CO_2 (kg/box)	28	33	-
NO_x (kg/box)	0,035	0,041	-
Ash/unburned material (kg/box)	6,39	7,52	-
Dust (10^{-5} kg/box)	4,7	5,6	-
Iron scrap (kg/box)	1,7	2	-
Landfill (m2)	0,15	-	1

Starting with the production of the box, the vacuum infusion has some emissions going out of the process, these are mostly styrene and unrecyclable plastic composite waste. Other than those there are very low emissions from the production phase. The inputs for the production are different raw materials (polyester resin, glass fibre and iron hinges) together with some amount of electricity. The largest difference from the production of the PE-box is the larger amounts of raw material going in. For most of the processes, there are transport of the inputs.

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[2] Bolur (2007)

[3] AQMD - South Coast Air Quality Management District (2015).

[4] Baumann et al. (1991)

The transport for the GFRP-box is a bit higher than the transport of the PE-box, this due to that the unit for transport is kg*km, and the GFRP-box weights more than the PE-box. Upstream processes of the production of the raw materials used and the energy used are a part of the background system and is therefore not addressed in this study. Data on the upstream processes are collected from the database *Ecoinvent*. As seen in table 3, all the inputs and outputs are the same for all waste scenarios.

Looking at the use phase, there are no specific emissions, the input and output are the same, one box, since it is assumed that the box will stay relatively intact in the use phase.

The emissions from the waste scenarios are calculated for combustion from the materials heat and combustion values, the combustion plants emission values of NO_x and the materials CO_2 emission factor. How the emissions from the combustion and recycling is calculated is described in Appendix B. For landfill, there are some amounts of electricity going into the process, together with some amount of diesel going in as well. Whereas for the combustion, the usage of electricity and heat is not accounted for since the process generates both heat and electricity and the amounts used has therefore been subtracted from the produced amounts in the output. Also, the transport looks different for the waste scenarios, where the combustion plant is located in Gothenburg and the landfill is located north of Gothenburg.

Production - vacuum infusion process (VIP)

Vacuum infusion, also called injection, is a type of method to produce strong, resistant, light weighted and practical composite materials in a closed process (PTO, 2013). Furthermore, the process gives a better work environment compared to traditional methods since the air pollutions (mostly styrene) are reduced, it removes the issue of air bubbles in the plastic and reduces the amount of waste (Sjögren, 2010; Holstensson et al., 2016; Hallabro Plast AB, 2013). The method is also described as "environmental friendly" due to the fact that the resin is applied in the vacuum, making the exposure of the resin minimal which reduces the different air emissions, for example VOC (for example styrene) and HAP, greatly (Moulded Fiber Glass Companies, 2017; Johnson, 2017a).

In figure 6, the vacuum injection process is described. First, a type of wax is applied on the mould as a release agent followed by a thin layer of gelcoat (Sjögren, 2010). The gelcoat will be the exterior of the box and will therefore give the box its colour, protection and surface finish. It is usually a mix of polyester and pigment, containing styrene of a maximum 35% (Johnson, 2017b). Then, either a prelaminate of thin carpets of glass fibre and vinyl ester (which is an active polyester) or a barrier coat is put on top of the gelcoat, this to protect against fibre penetration. After that, it is time to apply the fibre, usually it is a structural mat/weave. The structural fabric is applied in layers, normally a couple of layers of the fabric is needed to give the product its stiffness and strength. When the fibre mats are applied, two ducts are placed opposite to each other on the mould, one inlet for application of the matrix (the polyester resin) and one outlet where a vacuum pump is placed for the air to be sucked out. A vacuum cloth, made of polyamide or silicon, is placed on the top of the mould and the vacuum process can start (Sjögren, 2010). First a vacuum is produced by sucking out the air with the pump. When vacuum is achieved, the inlet where the matrix is located is opened and the wet matrix flows through the entire mould, from one end of the mould to the other. When the mould is filled with the matrix, the pump is stopped, the vacuum is reduced and the matrix is left to harden before the cloth is removed and the product can be removed from the mould (Sjögren, 2010; Svenska Tanso AB, n.y). The first part of this method is done quite quickly, the vacuum and filling of matrix only takes around 6 minutes. The hardening of the box takes about 45 minutes and the processing of the box takes around 10 minutes (Head of production at Glasfiberprodukter I Trehörningsjö AB, personal contact, March 28th, 2017).

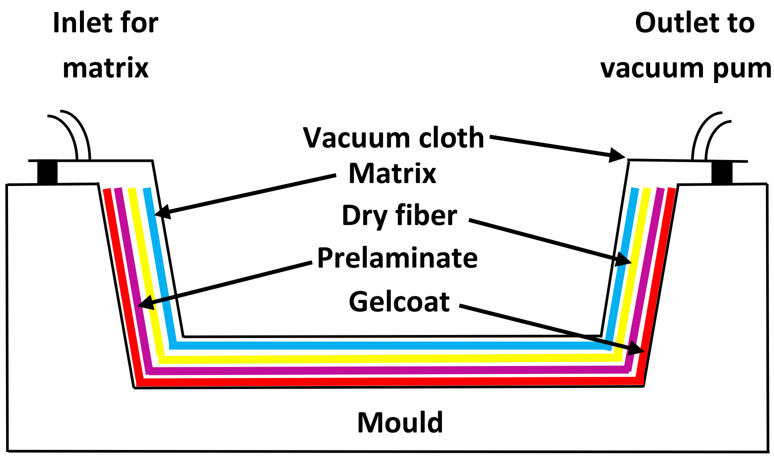

Figure 6. Schematic description of the production of glass fibre composite made with vacuum infusion process (Sjögren, 2010).

Waste management

GFRP is either combusted or put on landfill. Since it is a thermoset plastic, it cannot be remoulded or reshaped into new plastic material and is therefore not suited for material recycling. Furthermore, the glass fibre can't be completely incinerated and is therefore not always suited for combustion, making some amount of the waste go to landfill (Research Engineer at Swerea SICOMP M. Juntikka, personal contact, March 22nd, 2017; Fråne et al., 2012).

Health effects

A product made of glass fibre is not a health issue itself when it is intact, the issue of glass fibre lies in the production for the workers and when the product breaks and small particles of glass fibre is released into the air or to the skin. On an average, airborne glass fibre particles have diameter around 1µm (Eastes et al., 1996). Particles of glass fibre can give skin irritation when they penetrate the skin, causing *fiberglass dermatitis*, and eye irritations when in contact with the eyes (OSHA, 2005; Sertoli et al., 2000). Studies on dermatitis caused by glass fibre where made by Sertoli et al. (1992, 2000), where they concluded that the harmful effects where proportional to the diameter of the fibre, and reversed proportional to the length. The fibres where found harmful if they had a diameter greater than 4,5 µm (Sertoli et al., 1992).

Furthermore, if the fibre length is between 5µm and 80µm and with a diameter lower than 3µm, the particles reaches the lungs and can cause respiratory irritation such as asthma and *bronchopneumopathy* (Sertoli et al, 2000; OSHA, 2005). Eastes et al. (1996) showed that long fibres might lead to chronical effects since they remain in the lungs longer than shorter particles, and that it is not necessary the specific type of fibre that is harmful, but that it is the dissolution rate of the fibre that decides the harmfulness. According to some observations, lung cancer is a possible outcome from inhaling glass fibre dust, however this is demented in other studies (Sertoli et al., 2000). Several studies on rats by Dr. Mearl F. Stanton has showed that fibrous glasses cause *malignant mesenchymal neoplasms* (a type of cellular growth). The studies show that the dimensions and durability of the fibre is essential, where fibres with a diameter of 1,5µ or less and a length greater than 8µ where most probable to give *pleural sarcomas* (Stanton et al., 1977). Even though these studies are legit with proper experiments and scientists, one needs to keep in mind that some of these studies where done around 40 years ago and a lot has happened with the glass fibre material since then, especially with how it is handled and produced. But, the studies give an indicator that the fibres do have harmful qualities on living beings and needs to be handled with care. A more recent study by Ruegger (1996) has on the contrary showed that inhalation of glass fibre in rats does not result in tumours of the respiratory system. Therefore, there is not a clear correlation between inhalation of glass fibre and the risk of cancer, but that does not mean that it is not harmful to inhale and precautions should still be taken in the production of glass fibre products.

The polyester resin emits styrene when used in the production of the glass fibre composite, however, these emissions are limited due to the use of vacuum injections. It is debated if styrene causes serious health effects such as cancer. Some research has expressed concerns for the exposure of styrene, especially for those working everyday with the chemical. However, no clear and consistent evidence has been showed today that styrene can cause cancer. But, there are regulations on how styrene should be handled and demands on ventilation systems to minimize the exposure for workers (Molded Fiber Glass Companies, 2013). Furthermore, research by Groth-Marat (1993) and White et al. (1990) has showed that styrene can cause other health effects such as depression, fatigue with slower reaction times and detrimental psychiatric symptoms.

Another emission from the production of the GFRP box is aceton, which is used for cleaning the tools used in the production (Hallabro Plast AB, 2013). These emissions are estimated to be very low and is therefore excluded as emissions in this study.

There is a risk of health issues from the pollutants of a landfill that is leaked into the soil or water (Naturvårdsverket, 2017). However, for the boxes investigated in this study, the emissions are excluded since the assumption is that they stay relatively intact as a material at the landfill and therefore do not emit many pollutants.

5.2.3 Waste management

There are three main ways to treat plastic waste, through energy recycling (combustion), material recycling and landfill. What treatment that is used depends on the type of plastic and its composition with other materials. A thermoplastic (for example polyethylene) is easy to recycle and has a high-energy value, therefore this type of plastic is mostly combusted or material recycled (Group manager Textile, Plastic and Ceramics at Swerea IVF H. Oxfall, personal contact, March 15th, 2017). Thermoset plastic however (like the polyester in the GFRP-box) is mostly combusted, this since the plastic cannot be reshaped or remoulded into new material. Furthermore, if the plastic is a composite of different materials, like the GFRP-box (reinforced with glass fibre), the material is not always suited for combustion since the glass fibre cannot be combusted, and the material is then put on landfill (Research Engineer at Swerea SICOMP M. Juntikka, personal contact, March 22nd, 2017; Fråne et al., 2012).

In 2010 there was in total around 560 000 tonnes of plastic waste circulating in Sweden. In the overall total plastic waste generated, 58% was combusted for energy, 26% recycled for new plastic products, 14% used as fuel in the cement industry and 2% was put on landfill (table 4) (Fråne et al., 2012). Since the waste management processes investigated in this study is material recycling, energy recycling (combustion) and landfill, the category "fuel in the cement industry" will be excluded, and the amount will instead be calculated as energy recycling (table 4). For the PE-box, landfill will not be included, therefore the amount for landfill will be added to combustion. For the GFRP-box, recycling is not included as a management process, therefore the percentage for recycling will be divided over landfill and incineration (table 4).

Table 4. Distribution of plastic waste circulating in Sweden 2010 (Fråne et al., 2012). The percentage are adjusted depending on the waste management options for the two boxes separately. For both boxes, the heading "fuel" is not included and the percentage is instead added to combustion. For the polyethylene box, the percentage from landfill is added to combustion and for the glass fibre composite box, the recycling percentage is divided over both landfill and combustion.

	Combustion	**Recycling**	**Fuel**	**Landfill**	**Total**
Amount (tonnes)	320 000	144 000	80 000	12 000	556 000
Amount (%)	58%	26%	14%	2%	
Without fuel					
Amount (%)	72%	26%	0%	2%	
Polyethylene					
Amount (%)	74%	26%	0%	0%	
Glass fibre composite					
Amount (%)	85%	0%	0%	15%	

It is in the inputs and outputs for the different waste scenarios where the differences between the boxes are largest, this due to that the GFRP-box can't be material recycled and that it has a lower energy value when combusted and more ash/unburn material is produced. It is the differences in the waste scenarios that contributes to many of the differences in emissions from the two boxes since the GFRP-box is combusted or put on landfill and the PE-box can be recycled and combusted, with a higher production of heat and electricity from the combustion.

Energy recycling (combustion)

In a large waste-to-energy plant, electricity and district heating can be extracted from the condensed energy in the smoke and from the burning itself when waste is combusted (at around 1000°C). The slag (waste that has not been burned) is sorted into metals and ash for building material. The fly ash is mixed with sludge from the electrostatic precipitator and bag filters to produce a stable, leak free, cement-like material that is put on landfill (Renova, 2013).

The emissions to air produced in the combustion is cleaned with electric filter, washing reactor, condensation reactor, barrier filters (with active carbon) and sometimes a catalytic cleaning for nitrogen oxides. Furthermore, sulphur oxides are reduced with a separate wet cleaning step (Renova, 2015). There are many different emissions emitted from a waste-to-energy plant, what type of emissions depends on the waste combusted. For the incineration of polyethylene and glass fibre reinforced plastic, the largest emissions are assumed to be CO_2, NO_x, dust and ash, therefor it is these emissions that will be encountered for in the study.

In this study, the waste-to-energy plant used as a reference is Renova AB's plant Sävenäs, located on the edge of Gothenburg in Kviberg. The energy produced from Sävenäs, that is distributed out to the municipality (the net energy), consist of 88% district heat and 12% electricity (Renova, 2015). Since these values are the net flow, the heat and electricity needed for the plants processes are already accounted for and therefore the energy usage for the incineration is not included as an input.

GFRP are mostly incinerated due to the issue of material recycling of thermoset plastic and composite. However, they usually have a high percentage of inorganic material and has therefore a quite low energy content, which makes it not that profitable to burn for energy. Furthermore, the glass content cannot be incinerated and needs to be dealt with in other ways, normally it is put on landfill (Skrifvars et al., 2013).

Material recycling

Depending on the type of recycling method that is used, the inputs and outputs will differ. But in general, the traditional recycling methods for plastics are not highly energy intensive, especially if you compare to the energy needed for the production of virgin plastics (AlMa'adeed et al., 2011).

- *Polyethylene*

When recycling polyethylene, the material needs to be clean, no other particles and material can be present to be able to produce new polyethylene granulates. The material can be cleaned and filtrated in a process called melting filtration which is quite cost efficient and is cheaper compared with virgin material (Senior scientist polymer processing at Swerea IVF M. Strååt, personal contact, March 14th, 2017). According to Swerec, LDPE that comes into them is identified, sorted into different categories, cleaned, processed and distributed to the market again for the production of new plastic products (Swerec, 2015). The problem in today's recycling of plastics, according to Henrik Oxfall at Swerea IVF, is to find buyers of the recycled plastics to use in new plastic products. He says that the reason for why most plastics are being burned today is that the demand of recycled plastics is to low and therefore there are no economic value in material recycling of plastics.

If the plastic has contaminations in the form of hinges, it can be hard to recycle the product since the hinges needs to be removed before the plastic can be processed (Industrial Design Engineer at Stena Recycling AB T. Flink, personal contact, March 10th, 2017). In the case of the polyethylene box studied, the hinges are integrated in the plastic and made of aluminium, they are easy to remove which makes the possibility of recycling good (Västia Plastindustri AB, n.y). It is possible to crush the box, remove the hinges with a magnet and then recycle the plastic. However, this would not be economically profitable since the price of recycle PE is very low compared with the virgin PE, and therefore this is probably not done in most municipalities. If the hinges are not removed, the box will most likely be incinerated (Industrial Design Engineer at Stena Recycling AB T. Flink, personal contact, March 10th, 2017).

In the material recycling processes of plastics, around 20% of the plastic materials are lost and used for energy recycling instead, giving the recycling an efficiency of 80% (Fråne et al., 2012). However, in this study the recycling will be calculated as 100% efficient to simplify the comparison between the different waste scenarios.

- *Glass fibre reinforced plastic*

Glass fibre reinforced plastics can be either recycled mechanically, chemically or thermal (Sjögren, 2010). The most common one are thermal recycling, where they are grinded and burned for energy (combustion) as described below (Process Engineer at Renova AB L. Detterfelt, personal contact, March 6th, 2017). Other than incineration, the composite can be grinded and used as filling in for example building materials and roads, this is a type of mechanical recycling (Skrifvars et al., 2013; Sjögren, 2010). In difference from a thermoplastic like polyethylene, the plastic resin used in the GFRP box studied is a thermoset plastic which means that the plastic itself cannot be reshaped or remoulded (material recycled) into new materials (Johnson, 2017c). The fibres can be recovered by burning the composite on a fluidised bed, however this method is not yet commercial used due to the low economical value in recycled fibres (Pickering, 2006).

Recent studies have suggested different methods for recycling GFRP, a type of chemical recycling where the material is degraded into low molecular compounds with heat or solvents, for example with hydrolysis or pyrolysis (Sjögren, 2010). For example, Skrifvars et al. (2013) studied a method called microwave pyrolysis, which recycles the composite by heating the material with microwaves, without the presence of oxygen, and through that produce gas and oil, and at the same time separate out the glass fibre. The recycled material will thus not give as high mechanical qualities as virgin glass fibre would, this du to that its “sizing” is degraded. Furthermore, the length if the glass fibre is affected by the pyrolysis, they become brittle and degrades into shorter fibres (Skrifvars et al., 2013). This method is not commercially used today since the cost is to high compared to what is earned when selling the material (Senior scientist polymer processing at Swerea IVF M. Strååt, personal contact, March 14th, 2017).

- *Aluminium*

The hinges made of aluminium will most likely be material recycled, this due to the fact that it is more profitable to recycle aluminium than to produce new since the energy use for the production of virgin aluminium are very high, up to 95% energy can be saved with recycling processes (Nilsson – SÖRAB, 2007; Samuel, 2003).

Landfill

Landfill is a waste treatment method that becomes less common. Spreading of pollutants through the leachate water, where rainwater is pressed through the landfill and is polluted by the material, present is a big issue. Pollutants can be spread to the environment in the form of gases, particles and dissolved in water. One of the biggest emissions to air is methane gas, which is produced when the organic material in the landfill degrades. In difference to combustion and material recycling, the method gives nothing back in the form of new material or energy. The risk of leakage from the landfills are high, especially for older landfills where the ground and surface water is not always separated and pollutants can therefore contaminate them (Naturvårdsverket, 2017). For the two street sandboxes investigated, the emissions from landfill are assumed to be very low. Since the PE-box has a high energy and recycling value, it will most likely not be put on landfill. The GFRP-box however does not have such good energy value, the recycling is not yet commercially used and glass fibre can’t be combusted. Therefore, some amounts of the GFRP-boxes will most likely be put on landfill. The direct emissions from landfill are assumed to be very low for the GFRP-box since the material won’t degrade rapidly, these emissions are therefore discarded in this study. The emissions that has an impact from the landfill are the ones connected to the electricity use and diesel consumption of the vehicles and machines used at the landfill site.

5.2.4 Transport

For the two boxes, the transport differs in two ways. First, the weight of the boxes is different, the PE-box weights 23,66 kg and the GFRP-box weight 35 kg. This has an impact on the emissions from the transport since the unit is kg*km. Second, since both the raw materials used and the waste management are different for both the boxes, the length of the transport also varies. In table 5, the distance and locations for both boxes respectively are displayed.

Table 5. Distance and location for the transport in all processes and flows for both boxes. The flows included in processes total distance are italic.

	Distance (km)	From	To
PE-box			
Production	1229		
-PE-granulates	*1089*	Gravendeel	Munka-Jungby
-Al-hinges	*140*	Bredaryd	Munka-Jungby
Use phase	186	Munka-Jungby	Gothenburg
Combustion	5,8	Gothenburg	Kviberg
Recycling	296		
-to	*145*	Gothenburg	Bredaryd
-from	*151*	Bredaryd	Munka-Jungby
GFRP-box			
Production	1415		
-polyester resin	*1043*	Europe	Munka-Jungby
-glass fibre	*186*	Gothenburg	Munka-Jungby
-iron hinges	*186*	Gothenburg	Munka-Jungby
Use phase	186	Munka-Jungby	Gothenburg
Combustion	5,8	Gothenburg	Kviberg
Landfill	8,9	Gothenburg	Hisings kärra

Health and environmental effects (from burning of fossil fuels)

The health effects of air pollutants depend on many different factors, and it is not completely certain exactly what the effects are. The difference in impact is decided by how long the exposure is, how much pollutant that is present in the exposure, the composition of the pollutants and the mixture of pollutants in the exposure. Some pollutants cause respiratory issues, nausea or skin irritation, while other can have more serious effects such as cancer and birth defects (Kampa et al., 2007).

Vehicles has an incomplete burning of fossil fuels, this combustion releases different type of pollutants that differ greatly in for example chemical composition, transport range, persistence in the environment, reaction properties etc. (Kampa et al., 2007).

NO_x is produced in e.g. cars and industries where carbon oxides are combusted at high temperatures producing NO (Naturvårdsverket, 2016a). NO is emitted and quickly reacts with ozone and forms NO_2, which in the atmosphere is an important factor for ozone depletion (Kampa et al, 2007). NO_x causes acidic rain which leads to acidification of water, forest and soil. It also causes problems with the respiratory system such as asthma (Naturvårdsverket, 2016a). Furthermore, high levels of NO_x can reduce crop yields and plant growth by damaging the plants foliage (Queensland Government, 2016).

CO is formed by incomplete combustion of fossil fuels and can, if the emissions are very high at a small area, lead to heath issues such as lower oxygen uptake in the blood and symptoms of vascular spasm (Naturvårdsverket, 2016b).

VOC are easily evaporated, therefore their name, and are for example emitted from vehicles brake pads (Naturvårdsverket, 2016c). Benzene is a type of VOC and is said to lead to cancer, for example leukemia. Furthermore, both VOC and CO contribute to the production of ground ozone (Länsstyrelsen – Blekinge län, 2005). Methane (CH_4) is a type of VOC, but in difference of most VOC, it does not contribute much to ground level ozone or smog, instead it is one of the most dangerous GHG gas since it has a lifespan of around 10 years and a GWP 21 times higher than CO_2 (Scottish Environment Protection Agency, n.y).

Heavy metals are also bio-accumulative since they cannot be destroyed or degraded. They are released into nature through for example combustion and vehicles brake pads (Kampa et al., 2007; Naturvårdsverket, 2016c).

Particulate matter (PM) is a name for the particles in air pollutions, which can vary in size, composition and origin (Kampa et al., 2007). PM can consist of different compositions; metals, ions, organic compounds and reactive gases are some examples of the most common ones. Depending on their size, surface diameter, number of particles and the composition, the particles has different effects on health and nature. Particles smaller than 2,5um is called $PM_{2,5}$. These particles could be very small and has therefore the possibility to reach further down the respiratory system and reach the lung alveoli. Particles smaller than 10um is called PM_{10}. These are larger than $PM_{2,5}$ and will deposit in the upper part of the respiratory system when inhaled. In general, one can say that the smaller particles are more hazardous due to their possibility to enter further down the respiratory system and through tissues (Kampa et al., 2007). $PM_{2,5}$ can be transported long distance and are therefore most common in south of Sweden, closer to Europe, but also in larger cities where the traffic is higher. PM_{10} originates from wear and tear of the streets and tires, mostly caused by spike tires (Naturvårdsverket, 2016d). A study by McCreanor et al. (2007) showed respiratory effects in persons with different levels of asthma when exposed to heavy traffic on a short term. In addition to exposure of fine particles (<2,5 µm) on a heavy traffic road, they showed on exposure of elemental carbon and NO_x (McCreanor et al., 2007). Studies by Per Gustavsson has indicated that continuous exposure of particles from fossil fuel combustion emissions gives a higher risk to develop lung cancer and heart attack (Karolinska Institutet, 2015).

5.3 Life Cycle Impact assessment (LCIA)

The LCIA is divided into 5 sub-headings, depending on the waste scenario. First, the three different scenarios are addresses, starting with an overview of the different impacts from each box's processes compared to each other. This is followed by a more detailed evaluation of the individual processes of each box. After, the scenarios are compared with each other for each box respectively, to better show on which of the scenarios that has the highest impact. Last, the heat and electricity generated from the combustion is assessed to determine if it is better to burn and use the heat and electricity produced or if it is better to use natural gas and electricity from a Nordic residual mix.

5.3.1 Waste scenario 1 (WS1)

Table 6 shows the total emissions from the boxes on each impact category. The difference between the boxes can also be seen in figure 7, where the GFRP-box impacts are set to 100% and the PE-box impacts are calculated in relation to the GFRP-box impacts.

For Waste Scenario 1 (PE: 74% combustion and 26% recycling, GFRP: 85% combustion and 15% landfill) the total impact on climate change is for one PE-box 104 kg CO_2-eq and for one GFRP-box 256 kg CO_2-eq, a difference of almost 60%. The impact on stratospheric ozone depletion is for the PE-box $4{,}5 \cdot 10^{-6}$ kg CFC-11-eq and for the GFRP-box $23{,}8 \cdot 10^{-6}$ kg CFC-11-eq, giving the GFRP-box around 80% higher impact. For acidification, the impact from the PE-box is $20 \cdot 10^{-2}$ kg SO_2-eq and from the GFRP-box $85 \cdot 10^{-2}$ kg SO_2-eq, here the impact from the PE-box is around 25% of the impact from the GFRP-box. Last, the difference of the impact on human toxicity between the boxes is the largest one, where the PE-box has an impact less than 10% of the impact from the GFRP-box. From the PE-box its 23 kg 1,4-DCB-eq and from the GFRP-box its 286 kg 1,4-DCB-eq. All the emissions are calculated from all the processes in one box's lifecycle, including upstream and downstream processes. The lifetimes of the boxes are for the PE-box 45 years and for the GFRP-box 20 years.

Table 6. Comparison between the two boxes, when the waste management looks like it does today, with 74% combustion and 26% material recycling for the PE-box and 85% combustion and 15% landfill for the GFRP-box.

	Climate change (kg CO_2-eq)	**Ozone depletion** (10^{-6} kg CFC-11-eq)	**Acidification** (10^{-2} kg SO_2-eq)	**Human toxicity** (kg 1,4-DCB-eq)
Polyethylene box	104	4,5	20	23
Glass fibre box	256	23,8	85	286

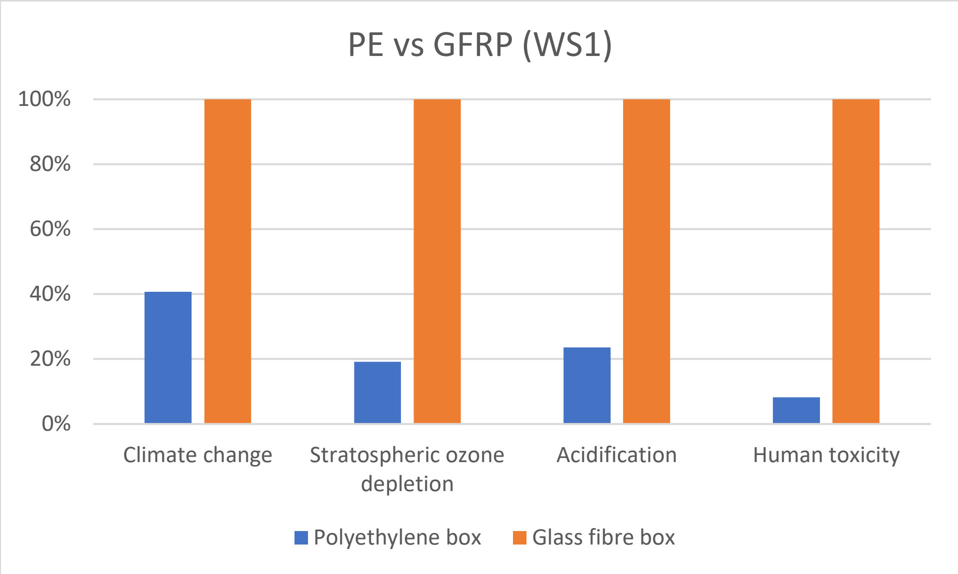

Figure 7. Comparison between the impacts of the two boxes, when the waste management looks like it does today. For the PE-box, the waste management is 74% combustion & 26% recycling. For the GFRP-box, it's 85% combustion & 15% landfill. The figure shows the relation between the different impacts from the boxes on each impact category. GFRP-box is put to a 100% and the PE-box impacts are calculated in relation to the impacts of the GFRP-box.

Figure 7 makes it clear that the impacts from the GFRP-box's lifecycle is more than 50% higher than the PE-box for all the impact categories. What is not clear is why this is, and where all the emissions that causes these impacts comes from. To be able to answer this, we need to look closer on both of the boxes individual processes and their emissions.

Figure 8 shows the impacts from the PE-box on all the impact categories, and figure 9 shows the impacts for the GFRP-box. The bars show the amount of impact from the different processes, where the production process is split up into sub-bars to show where the impact from the production originates from. Each bar has a percentage on top of them to show how large each process impact is on the total impact from the box. Not all the impacts from the different flows in the processes are displayed in the charts, only the ones that has a large impact are present. All the impacts from both processes and their flows are shown in Appendix A. The total transport bar includes all transport in the whole product system, therefore the transport percentage is a bit misleading since the transport in the processes already is accounted for in the processes total percentage, only the transport in the use phase is only represented in the total transport column. To make it clear that the transport bar is different from the other bars, its marked with stripes. Therefore, the sum of the percentage of the processes (production, combustion and recycling) is not 100%, since a smaller part of the transportation in the use phase is not accounted for.

PE-box

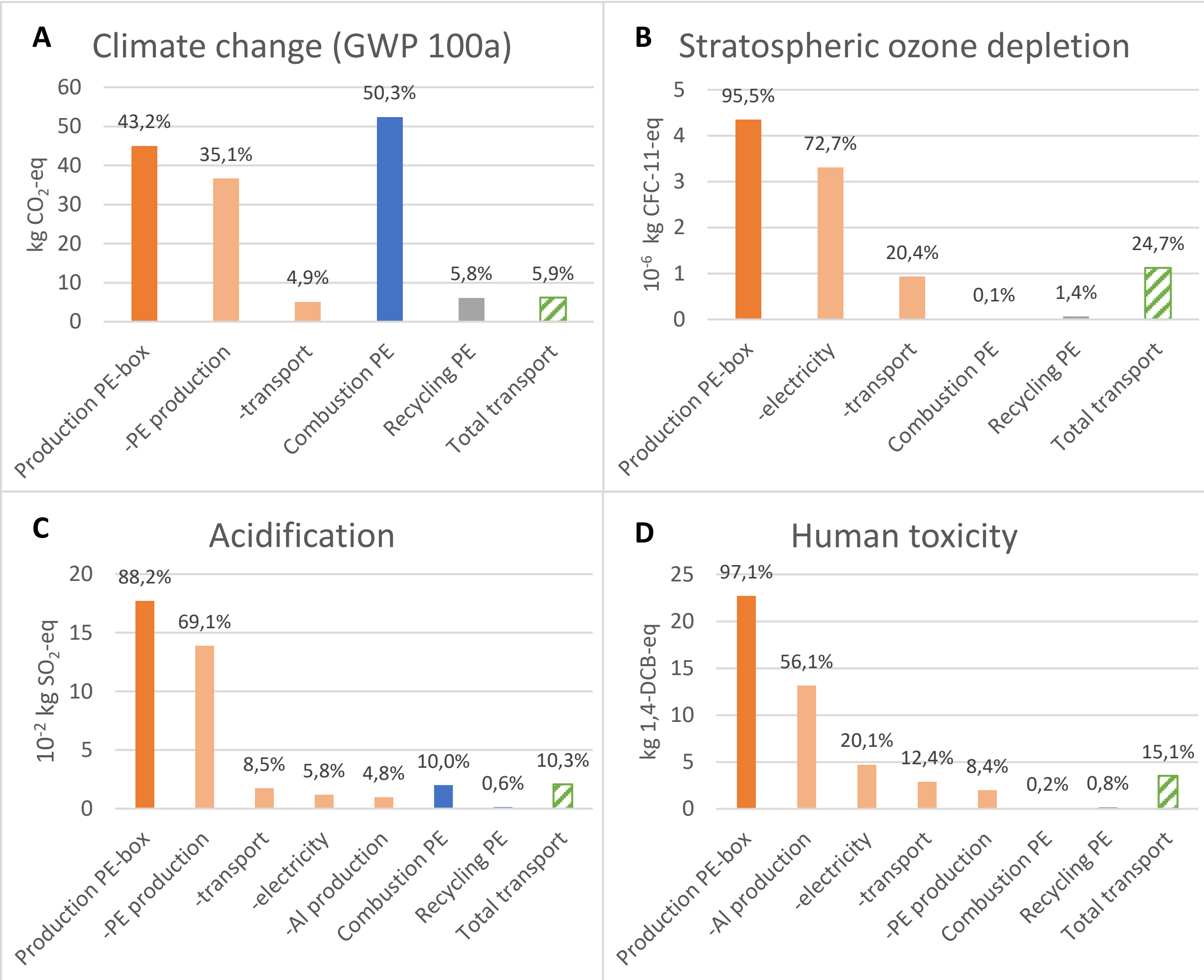

Figure 8. Overview of the different processes individual impact on the four impact categories. The columns that have a darker colour of blue and orange are the process itself that are included in the LCA. The lighter columns of blue and orange are the flows or upstream processes different contribution to the impact. The percentage on top of each bar represents the part of which each process contributes to the total impact from the box's lifetime. The total transport includes all transport in the whole product system, therefore the transport percentage is a bit misleading since the transport in the processes already is accounted for in the processes total percentage, only the transport in the use phase is only represented in the total transport column. The bar for the total transport is marked with stripes to make it clear that it differs from the other bars.

A - Climate change

The biggest impact comes from the combustion of the PE-box (50,3%) where it is the combustion itself that contributes to most of the GWP-emissions. These emissions are calculated from the emission factor and heat value of PE. The production of the PE-box stands for 43,2% of the impacts on climate change, where the biggest contributor is the upstream emissions from the production of the polyester granulates used (35,1%). Smaller amounts come from the electricity and transportation involved in the production. For the recycling (5,8%), the impact comes from the process itself which is calculated from data on emissions from other studies on recycling.

B - Stratospheric ozone depletion

The production of the PE-box stands for 95,5% of the impact, where the electricity used is the biggest contributor (72,7%), mostly due to nuclear power and the uranium used there. Transportation is a quite large contributor, with 24,7% impact in total, where it is the diesel combustion itself that has the largest impact. Both recycling and combustion has a very low impact on ozone depletion, where the only contribution is from the smaller amount of transport.

C - Acidification

Similar to climate change, the largest impact comes from the production of the PE-box (88,2%), more specific the production of polyethylene granulates (69,1%) and the transportation (8,5%). Smaller contributions come from the electricity production (5,8%) and the Al-production (4,8%), where aluminium oxide is a large contributor. The combustion stands for 10% impact where it is the burning itself that emits emissions that has an impact on acidification. The recycling has almost no impact on acidification, only 0,6%. Transportation has 10,3% impact on acidification.

D - Human toxicity

Same as for the other impact categories, it is the production of the PE-box (97,1%) that has the largest contribution on the human toxicity. But as for the others, it is not the production itself that gives the large impact, it is the upstream processes that has a large contribution. Here, it is the aluminium production that has a very large impact (56,1%), followed by electricity (20,1%) where the impact originates from nuclear power. The production of PE-granulates stands for a contribution of 8,4% that originates from “average incineration residue” according to *Econinvent*. Transportation has an impact of 15,1% where the largest impact is break wear emissions. Combustion and recycling has very low impact on human toxicity.

GFRP-box

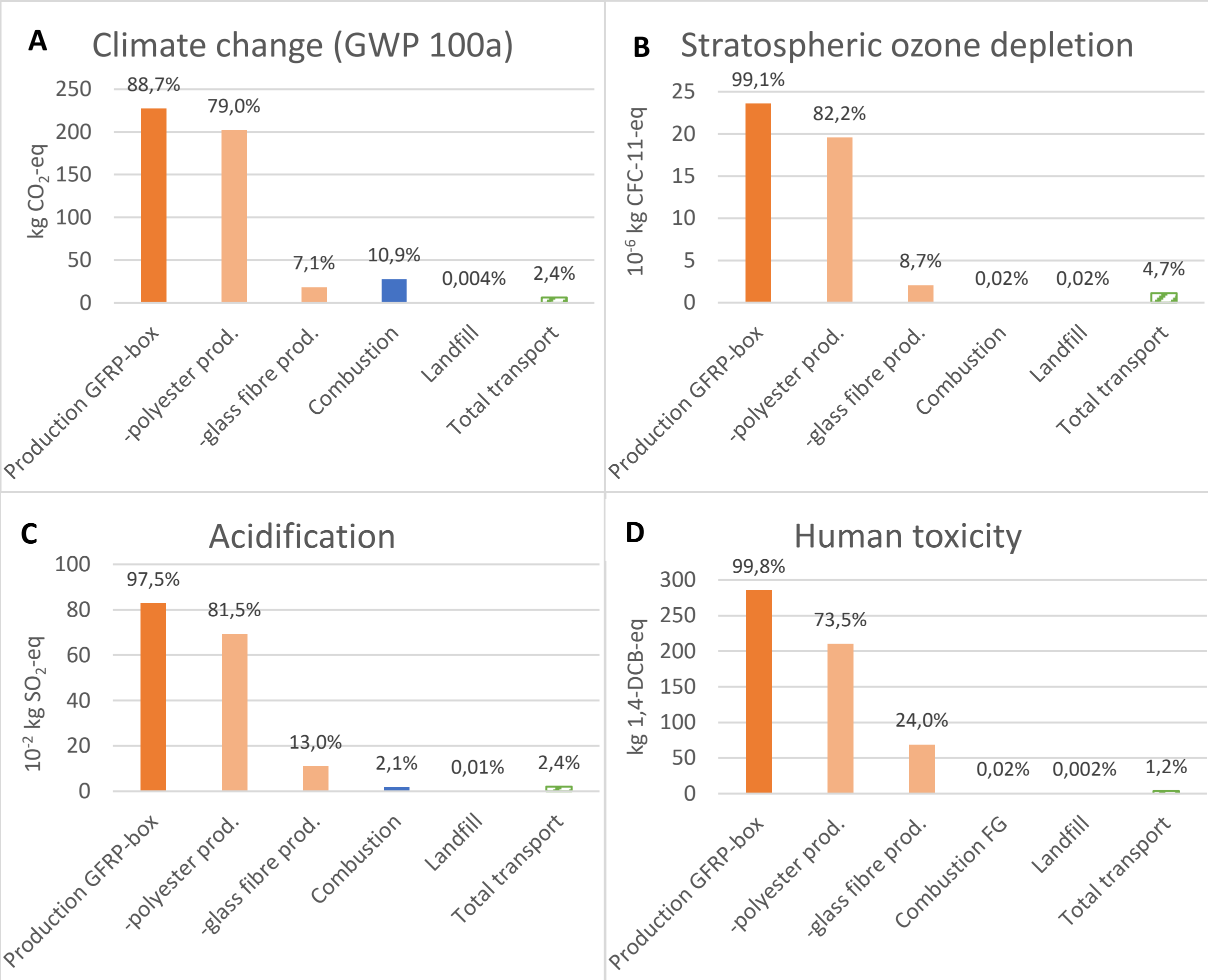

Figure 9. Overview of the different processes individual impact on the four impact categories. The column that has a darker colour of orange is the process itself that is included in the LCA. The lighter columns of orange are the flows or upstream processes different contribution to the impact. The percentage on top of each bar represents the part of which each process contributes to the total impact from the box's lifetime. The total transport includes all transport in the whole product system, including the ones from the processes already displayed. Therefore, the transport percentage is a bit misleading since the transport in the processes already is accounted for in the processes total percentage, only the transport in the use phase is only represented in the total transport column. The bar for the total transport is marked with stripes to make it clear that it differs from the other bars.

A - Climate change

The production of the glass fibre reinforced plastic box (GFRP-box) stands for 88,7% of the impact on climate change, where the upstream production of polyester resin has the largest impact (79%). It is the adipic acid, phthalic anhydride and propylene glycol in the polyester resin production that contributes to the high impact on climate change. Adipic acid is a strong GHG since it emits a lot of NO. The production of glass fibre has an impact of 7,1%. The combustion has an impact of 10,9% where it is the incineration itself that has high GWP. The transportation is only a very small contributor (2,4%), alongside with landfill (0,004%).

B - Stratospheric ozone depletion

The production of the GFRP-box contributes with 99,1% of the emissions that has an impact on the ozone depletion. It is the polyester resin production that has the largest effect (82,2%), mostly due to the propylene glycol, but also smaller amounts from the adipic acid, acetic anhydride and phthalic anhydride. The glass fibre production contributes with 8,7%, mostly from the production itself and the heat used (natural gas). The electricity stands for 4,1% of the impact, most emissions comes from nuclear power. Transport, landfill and combustion has hardly any contribution to the ozone depletion.

C - Acidification

The production of the GFRP-box has the largest impact on acidification, 97,5%, where the production of polyester resin stands for 81,5 % of the impact, this due to phthalic anhydride, propylene glycol, adipic acid and acetic anhydride. The impact from the glass fibre production (13%) originates from the production of the glass fibre itself together with the boric acid and heat (natural gas) used in the production. The transport, landfill and combustion does not contribute with much acidification.

D - Human toxicity

As for the other impact categories, it is the production of the GFRP-box that has the largest impact (99,8%), where 73,5% comes from the production of the polyester resin used. In the resin production, it is mostly propylene glycol that contributes with high impacts on human toxicity, followed by adipic acid and phthalic anhydride. The glass fibre production itself contributes to 24% impact. Combustion, landfill and transport has very low impacts on human toxicity.

5.3.2 Waste scenario 2 (WS2)

When comparing the two boxes in WS1, the waste management where shown to contribute to a large part of the difference. To be able to compare the differences in impact in a consistent way, the waste management need to be the same for the two boxes. Therefore, a comparison between the two boxes has been made for WS2, where both of the boxes are 100% combusted. Table 7 show the total impacts on each of the impact categories, where the GFRP-box has a much higher impact on all of the categories compared to the PE-box. In figure 10 the difference between the boxes is displayed, where we can see that for the climate change the GFRP-box has almost 50% higher impact. The PE-box has only around 20% of the impact of the GFRP-box for the ozone depletion and around 30% for the acidification. For the category human toxicity, the PE-box has only 10% of the impact compared to the GFRP-box.

Table 7. Comparison between the two boxes, when the waste management is 100% combustion.

	Climate change (kg CO_2-eq)	**Ozone depletion** (10^{-6} kg CFC-11-eq)	**Acidification** (10^{-2} kg SO_2-eq)	**Human toxicity** (kg 1,4-DCB-eq)
Polyethylene box	130	4,5	26	29
Glass fibre box	261	23,8	85	286

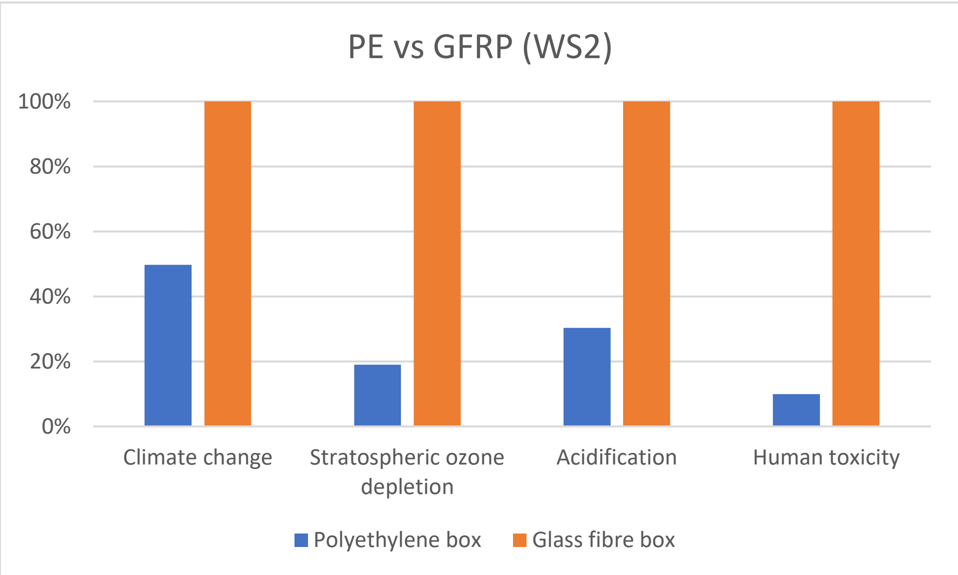

Figure 10. Comparison between the two boxes when the waste management is 100% combustion. The figure shows the relation between the different impacts from the boxes on each impact category. GFRP-box is put to a 100% and the PE-box impacts are calculated in relation to the impacts of the GFRP-box.

As for WS1, to be able to see where the emissions come from, we need to look closer on each box’s processes and their individual impact on the different impact categories. Figure 11 shows the individual processes for the PE-box and its impact on the four categories. Figure 12 shows the impacts from the GFRP-boxes processes. Only the flows in the processes that has a large impact are shown in the charts. All the impacts from both processes and their flows are shown in Appendix A. Each bar has a percentage next to them to show how large each process impact is on the total impact from the box. The origin of the emissions is the same as described in WS1, only the amounts vary.

PE-box

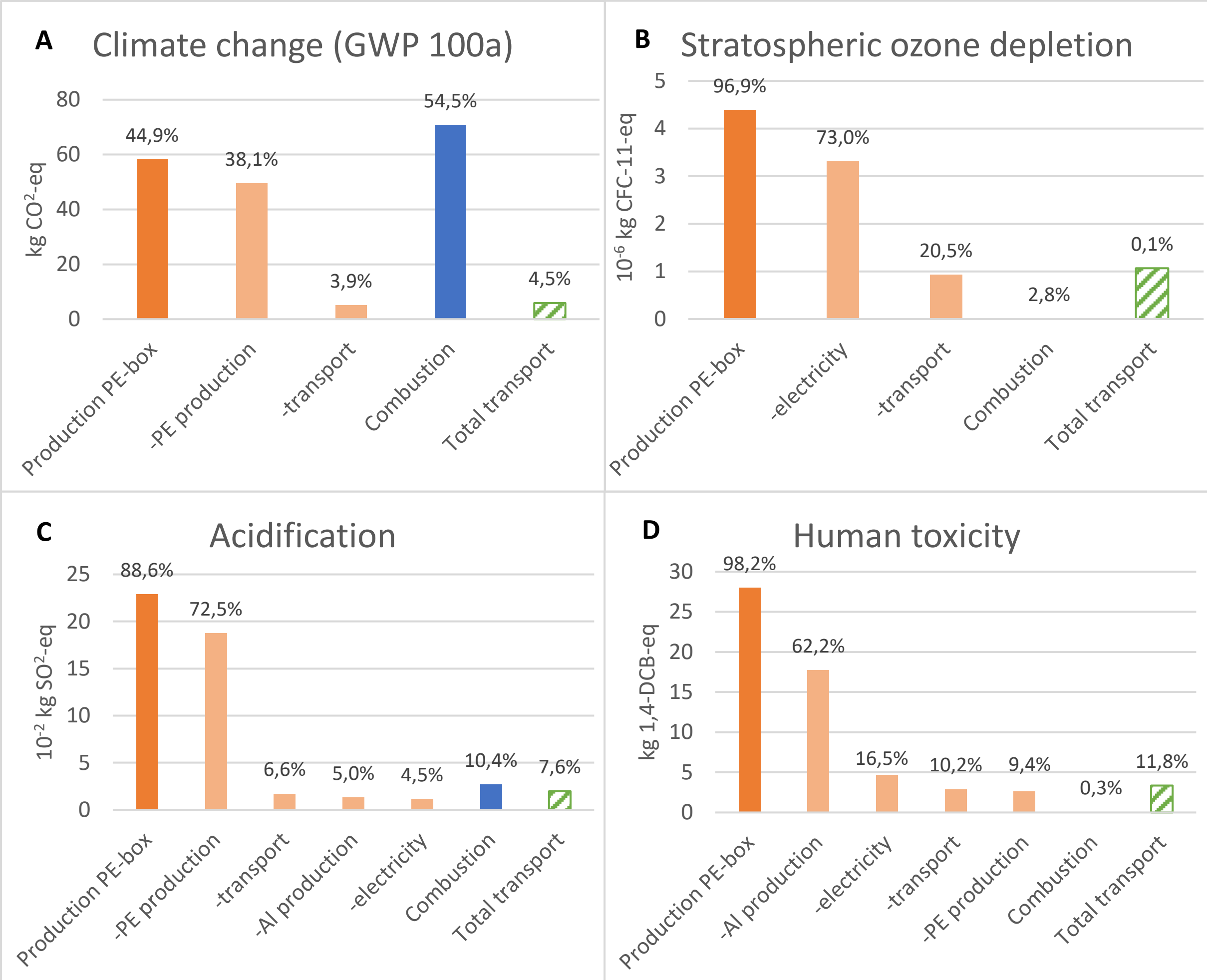

Figure 11. Overview of the different processes individual impact on the four impact categories. The column that has a darker colour of orange is the process itself that is included in the LCA. The lighter columns of orange are the flows or upstream processes different contribution to the impact. The percentage on top of each bar represents the part of which each process contributes to the total impact from the box's lifetime. The total transport includes all transport in the whole product system, including the ones from the processes already displayed. Therefore, the transport percentage is a bit misleading since the transport in the processes already is accounted for in the processes total percentage, only the transport in the use phase is only represented in the total transport column. The bar for the total transport is marked with stripes to make it clear that it differs from the other bars.

GFRP-box

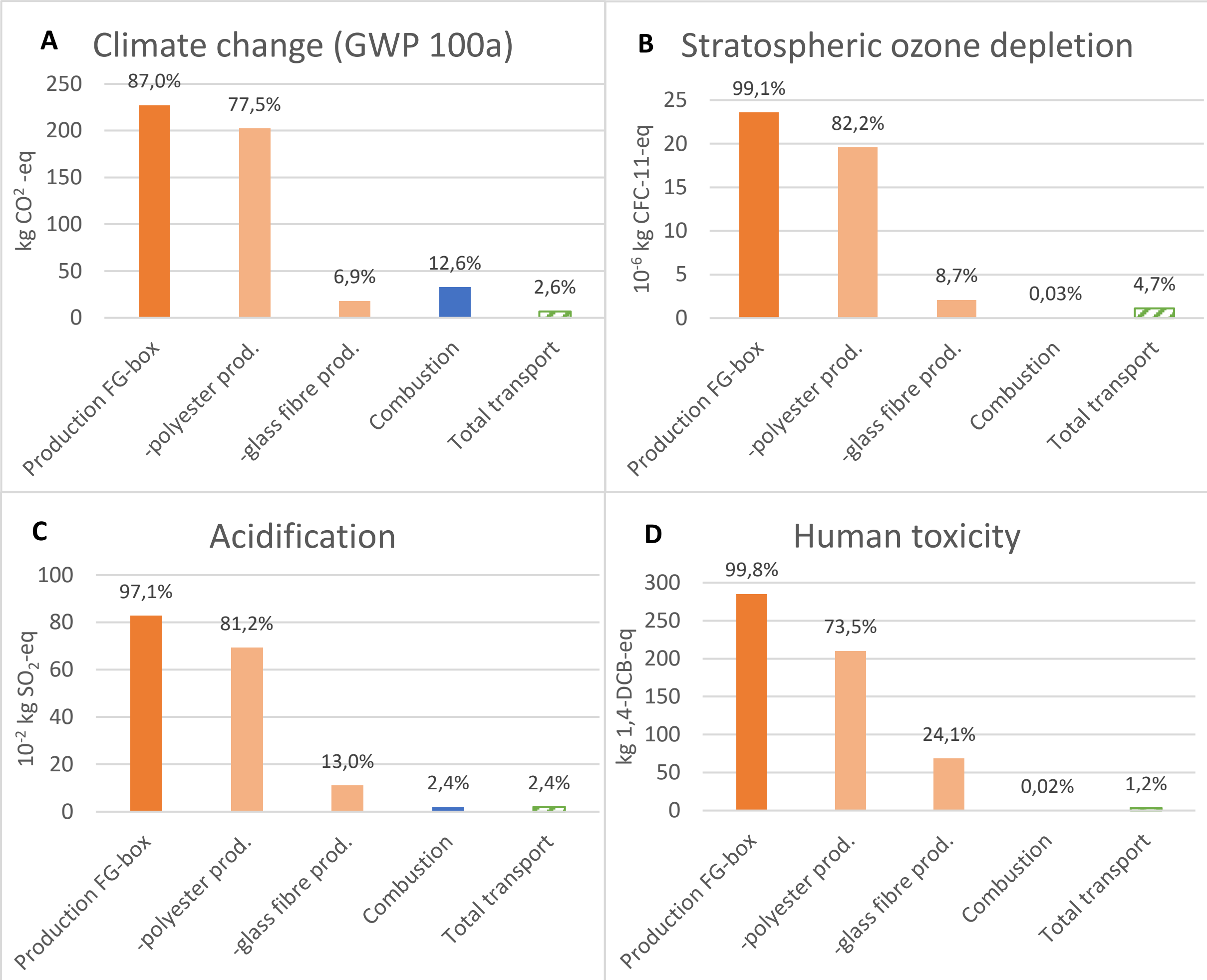

Figure 12. Overview of the different processes individual impact on the four impact categories. The column that has a darker colour of orange is the process itself that is included in the LCA. The lighter columns of orange are the flows or upstream processes different contribution to the impact. The percentage on top of each bar represents the part of which each process contributes to the total impact from the box's lifetime. The total transport includes all transport in the whole product system, including the ones from the processes already displayed. Therefore, the transport percentage is a bit misleading since the transport in the processes already is accounted for in the processes total percentage, only the transport in the use phase is only represented in the total transport column. The bar for the total transport is marked with stripes to make it clear that it differs from the other bars.

5.3.3 Waste scenario 3 (WS3)

There is no reason to compare the two boxes for this scenario since the waste management processes looks very different. This scenario is interesting to look at when comparing the different scenarios for each box individually. Therefore, a bar-chart is not made to compare the two boxes. However, bar-charts are conducted for each box individually to look at the different processes and their contribution to the impacts, as seen in figure 13 and 14. The origin of the emissions from the processes that causes the different impacts are the same as in WS1, only the amounts vary. The principles and design of the figures are the same as for WS1 and WS2.

PE-box

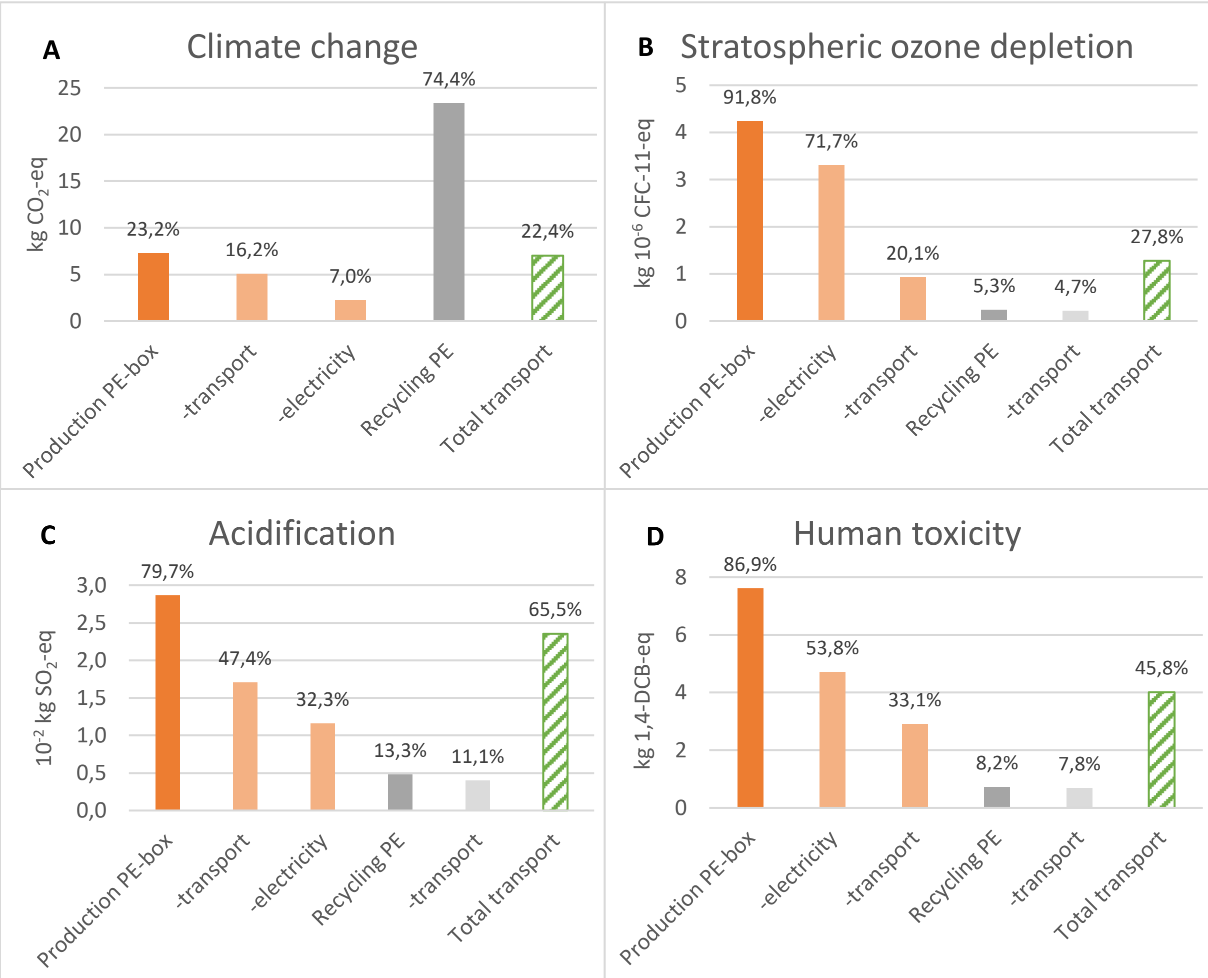

Figure 13. Overview of the different processes individual impact on the four impact categories. The columns that has a darker colour of orange and grey are the process itself that are included in the LCA. The lighter columns of orange and grey are the flows or upstream processes different contribution to the impact. The percentage on top of each bar represents the part of which each process contributes to the total impact from the box's lifetime. The total transport includes all transport in the whole product system, including the ones from the processes already displayed. Therefore, the transport percentage is a bit misleading since the transport in the processes already is accounted for in the processes total percentage, only the transport in the use phase is only represented in the total transport column. The bar for the total transport is marked with stripes to make it clear that it differs from the other bars.

There is a large difference on the size of the impacts in this waste scenario compared to WS1 and WS2. When there is 100% recycling of the box, in a closed-loop system, all plastic used in one box goes back to the production and is used instead of the virgin PE. Therefore, the emissions from the upstream processes of the virgin PE and virgin Al is zero. Since it for many of the impact categories has been showed to be the production of PE-granulates that was the biggest contributor to the impact, the charts for WS3 looks quite different.

A – Climate change
This is where the biggest difference from the other waste scenarios can be seen. Here it is the recycling process that generates most GHG that gives an impact on the climate change (74,4%) followed by production of the PE-box (23,2%) where it is the transport generating most emissions (16,2%). Important to notice is the amount of CO_2-eq, for WS3 the total GHG-emissions are just over 30kg, for the WS2 with 100% combustion it is almost 130kg. This shows how big of a difference the recycling can be on the environment. This will be discussed more in 4.1.4.

B – Stratospheric ozone depletion
The impact on stratospheric ozone depletion is similar to the other waste scenarios, where the production of electricity used in the rotational moulding of the box is the biggest contributor of CFC (71,7%), mostly due to nuclear power.

C – Acidification
It is the transport (65,5%) and electricity (32,3%) that are the largest contributors, somewhat similar to the other waste scenarios if excluding the PE production.

D – Human toxicity
The largest contribution comes from the electricity used in the production phase (53,8%), followed by transport (45,8%). Here the amount is much lower than WS1 and WS2 due to no use of virgin PE-granulates that was shown to have a large effect.

GFRP-box

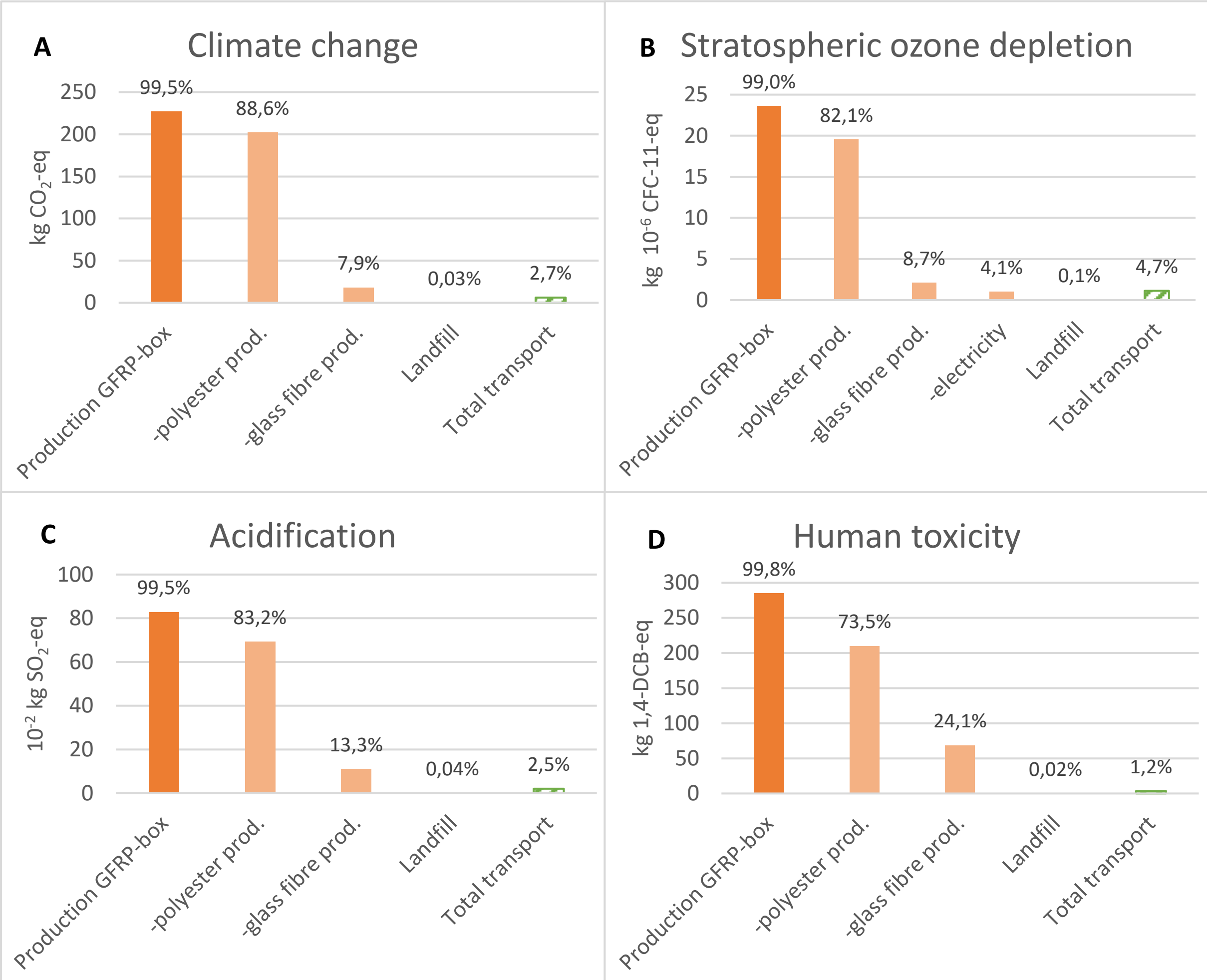

Figure 14. Overview of the different processes individual impact on the four impact categories. The column that has a darker colour of orange is the process itself that is included in the LCA. The lighter columns of orange are the flows or upstream processes different contribution to the impact. The percentage on top of each bar represents the part of which each process contributes to the total impact from the box's lifetime. The total transport includes all transport in the whole product system, including the ones from the processes already displayed. Therefore, the transport percentage is a bit misleading since the transport in the processes already is accounted for in the processes total percentage, only the transport in the use phase is only represented in the total transport column. The bar for the total transport is marked with stripes to make it clear that it differs from the other bars.

The biggest difference here compared to the other waste scenarios is the lack of emissions from the combustion. Mostly it can be seen in climate change where combustion is a large GHG-source. Other than that, the emissions originate from the same as in WS1 and WS2 and the largest contributors to the emissions are the same.

5.3.4 All waste scenarios

The impacts from the boxes look very different depending on their waste treatment, this is showed in figure 15 and 16.

PE-box

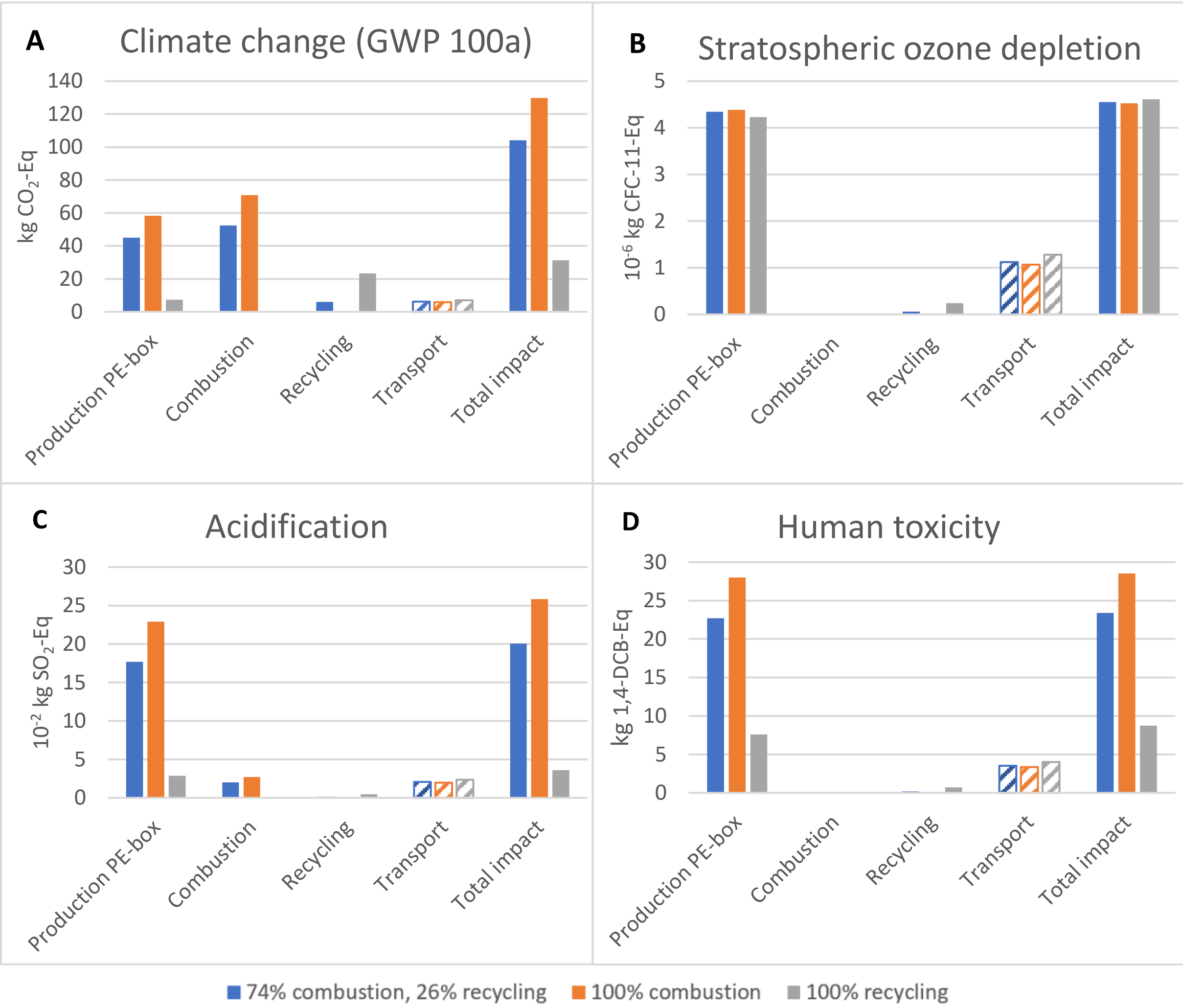

Figure 15. Comparison between the different waste scenarios, divided into the different processes and impact categories. The bars for transport is striped to clarify that most of the emissions from transport already is accounted for in the individual processes, the transport display is a summary of all transports in the whole lifecycle of the box.

There is a large difference between the different waste scenarios for the PE-box. The biggest differences are showed in climate change, acidification and human toxicity between WS2 (100% combustion) and WS3 (100% recycling). For climate change, the large difference in impact is due to the large amount of GHG-emissions from the combustion of the box and the emissions from the production of PE-granulates used in the production. For recycling, the emissions from the combustion is excluded, and the emissions from the production of PE-granulates are reduced to zero since there are no virgin PE used in this scenario, only recycled PE is used in the production. The recycling itself emits smaller amount of GHG.

The stratospheric ozone depletion impact is more or less the same for all the scenarios, this due to the fact that the emissions comes from the production of the box, more specific the electricity used and the transport, and the overall transport. The electricity used is the same for all scenarios, the transport varies only with smaller amounts.

Acidification comes mostly from the production of PE-granulates, giving the recycling scenario very low impact since no virgin PE is used. Some impact from the production of the box for the recycling scenario is present, this from the use of electricity and transport. For the combustion scenario, some amount of impact also comes from the aluminium production, this excluded in the recycled scenario since all aluminium used there comes from recycled aluminium. From transport, the contribution is more or less the same for all scenarios.

For human toxicity, large amount of the impact in the combustion scenario comes from the production of aluminium, therefore the impact from the recycling scenario is smaller since all aluminium used comes from recycled material. Some amounts also come from electricity use and transport, these flows are similar for all scenarios. There are emissions from the production of the PE-granulates used in the production process, giving higher impact for the combustion scenario, and no impact for the recycled scenario since no virgin PE is used there.

GFRP-box

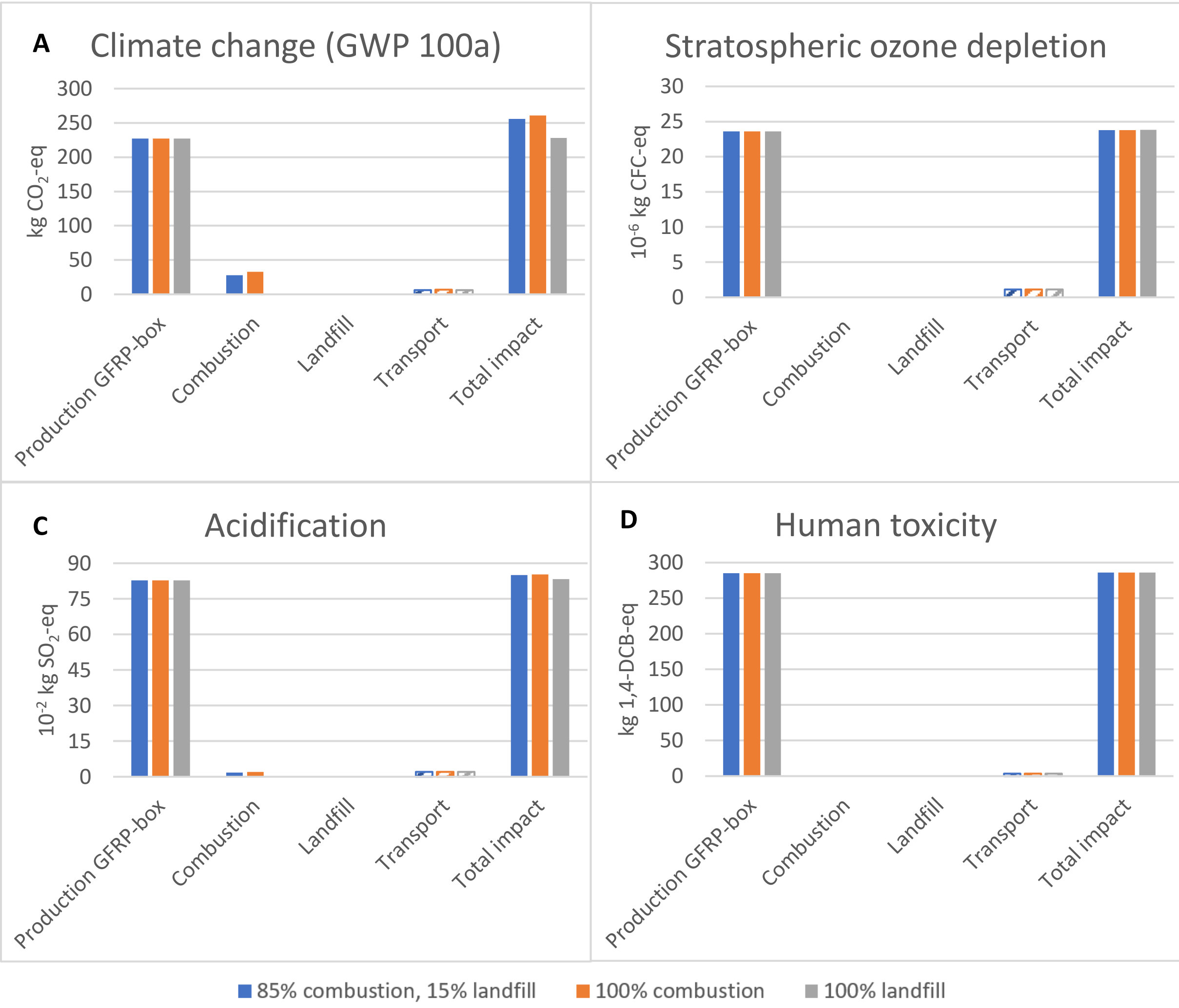

Figure 16. Comparison between the different waste scenarios, divided into the different processes and impact categories. The bars for transport is striped to clarify that most of the emissions from transport already is accounted for in the individual processes, the transport display is a summary of all transports in the whole lifecycle of the box.

The impacts from the different waste scenarios for the GFRP-box is not big, this since the inputs of raw material (polyester resin, glass fibre and iron) are the same for all scenarios, and it is in the production of these materials that the largest impacts lay. Some differences in impact can be seen in climate change from the emissions of GHG in the combustion process. However, these emissions are only around 10% of the emissions from the production of the polyester resin, and therefore the impacts do not vary in larger scales. Small difference can be seen between the scenarios for acidification, this due to the emissions from the combustion.

5.3.5 System expansion – heat and electricity from combustion

The impacts from the combustion of the boxes where shown to be high for the climate change category and some impacts were also showed for the acidification. However, the positive prospect of the combustion, where heat and electricity is produced, is not included as a positive outcome in the calculations. Therefore, we need to look at what is saved in terms of other sources of heat and electricity, to be able to say if the emissions from the combustion are in relation small or high compared to the alternative.

In this study, the district heat produced in the combustion was compared with natural gas and the electricity produced was compared with a Nordic residual electricity mix for Sweden (43% fossil energy, 41% nuclear energy and 17% renewable energy (Öresundskraft, 2016)).

Natural gas in Sweden has GHG-emissions of 69 g CO_2-eq/MJ, giving a total impact on climate change of 61,7kg CO_2-eq for the same amount of district heat produced when one PE-box is 100% combusted (Gode et al., 2011). Nordic residual mix has CO_2 emissions of 93,4g/MJ, giving a total emission of 11,4kg CO_2-eq for the same amount of electricity produced from the combustion and smaller "emissions" of nuclear waste (Öresundskraft, 2016). The total emission from producing new heat from natural gas and electricity from the Nordic residual mix is 73kg CO_2-eq (table 8).

Table 8. The CO_2-eq emissions from the combustion compared with the emissions from producing the same amount of energy from natural gas and Nordic-mix electricity.

	Amount (MJ)	**kg CO_2** (combustion)	**kg CO_2** (natural gas & Nordic mix)
PE			
Heat	893,5	-	61,6
Electricity	121,8	-	11,4
Total	1015,3	70,7	73,0
GFRP			
Heat	871,2	-	60,1
Electricity	118,8	-	11,1
Total	990,0	32,8	71,2

Comparing these emissions with the emissions from the combustion of the PE-box (the combustion process only, excluding the transport), which is 70,7 kg CO_2-eq, the emissions does not vary that much, only a bit over 1 kg CO_2-eq is saved by using heat and electricity from the combustion instead of natural gas and Nordic residual mix (table 8).

For the GFRP-box, the emissions of GHG from the combustion are 32,8 kg CO_2-eq. For the natural gas the total emission for the same amount of heat is 60 kg CO_2-eq and for the electricity it is 11 kg CO_2-eq, giving a total emission of GHG of 71,2 kg CO_2-eq. Compared with the combustion, the production of new heat and electricity is almost 40 kg CO_2-eq more (table 8). Why there is a bigger difference for the GFRP-box than for the PE-box is due to the lower energy value giving the box less energy for the same amount of material. This shows that there are benefits with using energy from combusted material instead of using energy from natural gas and Nordic residual mix.

5.4 Interpretation of results

Interpretations of the calculations and results, together with a discussion around these are addressed in the discussion.

5.4.1 Sensitivity analysis

The lifetime of the boxes is a big factor that changes the amount of impact quite rapidly. For the scenarios above, the lifetime of the boxes is not considered, which for the PE-box is 45 years and for the GFRP-box is 20 years. The PE-box has almost double the lifetime of the GFRP-box, 225% to be exact. To show on these differences, a sensitivity analysis has been conducted to compare the impacts from the boxes. Where the lifetime for the PE-box varies and the lifetime of the GFRP-box is the same, but is related to the changes of lifetime of the PE-box and therefore the number of boxes needed for the same amount as one PE-box changes, together with the emissions.

Figure 17 shows the impacts on each impact category for both boxes, for a time span of 45 years. Meaning that for this time span, one PE-box is needed (since the lifetime of it is 45 years) and 2,25 GFRP-boxes are needed (since the lifetime of it is 20 years), giving the GFRP-box 225% higher emissions than what is calculated in the different scenarios above.

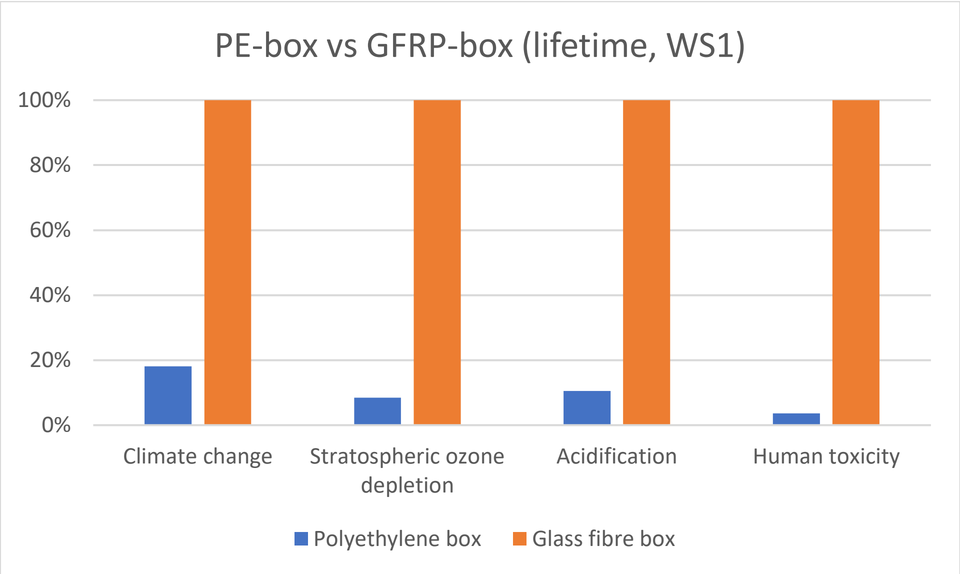

Figure 17. Comparison between the impacts of the two boxes when the lifetime is taken into consideration. The waste management is according to WS1. For the PE-box, the waste management is 74% combustion & 26% recycling. For the GFRP-box, it's 85% combustion & 15% landfill. The figure shows the relation between the different impacts from the boxes on each impact category. GFRP-box is put to a 100% and the PE-box impacts are calculated in relation to the impacts of the GFRP-box.

The difference in impact between the boxes becomes even greater when the lifetime is addressed. The largest difference is seen for human toxicity, where the impact from the GFRP-box is 96% greater than for the PE-box. For acidification and stratospheric ozone depletion, the difference is around 90% of the impact and for climate change its around 80% (figure 17).

Table 9 show the different time span used in the sensitivity analysis, and how the emissions from the GFRP-box varies with it. The lifetimes used are based on the highest and lowest lifetime of the PE-box given from the different sources, together with the mean value of the PE-box's lifetime and a value in between the mean and the high to give a better range of the analysis.

Table 9. Results from the sensitivity analysis. The impacts from both boxes are showed for each impact category. The emissions from the GFRP-box is divided into the different lifetimes of the PE-box. The emissions from the PE-box are consistent for the different time spans.

	Climate change *(kg CO_2-eq)*	**Ozone depletion** *(10^{-6} kg CFC-11-eq)*	**Acidification** *(10^{-2} kg SO2-eq)*	**Human toxicity** *(kg 1,4-DCB-eq)*
PE-box (all years)	104	4,5	20	23
GFRP-box				
26 years	333	31,9	110	372
45 years	576	53,5	191	643
75 years	960	89,2	319	1072
100 years	1280	119,0	425	1429

In figure 18, the results from the sensitivity analysis is showed, where the lifetime of the PE-box varies, making the number of GFRP-boxes needed vary and therefore also the emissions generated.

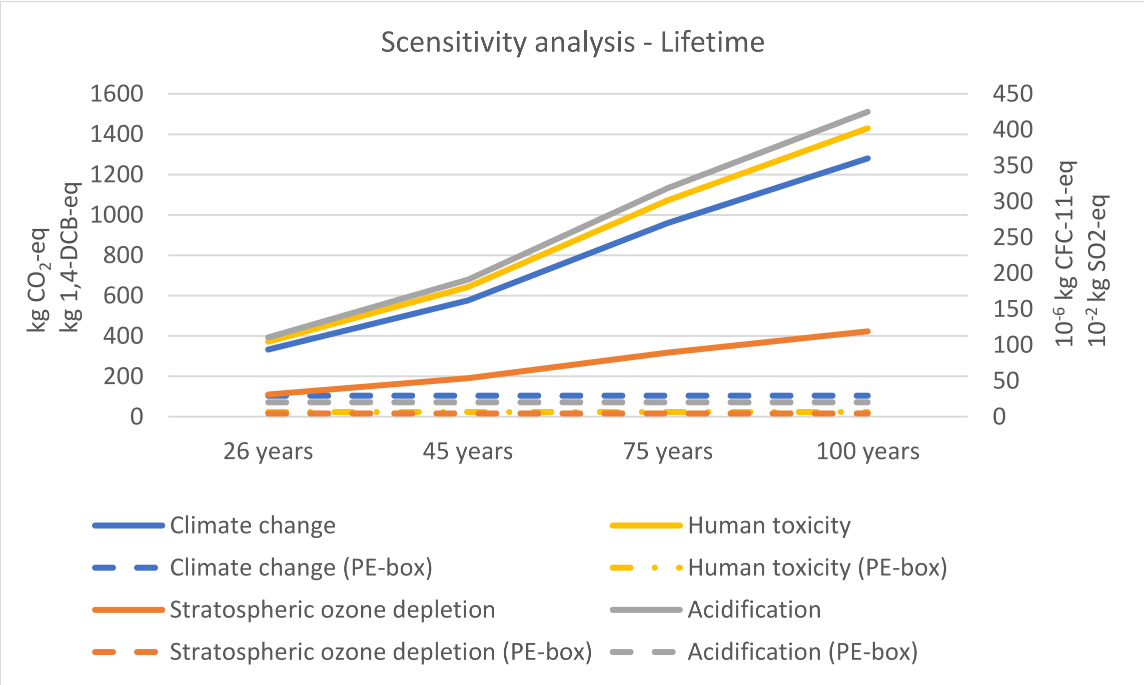

Figure 18. Results from the sensitivity analysis on different lifetimes for the PE-box, and the effects it has on the emissions from the GFRP-box when the lifetime is accounted for. For climate change and human toxicity, it is the left axis values that shows the amount of emission in kg CO_2-eq and kg 1,4-DCB-eq. For stratospheric ozone depletion and acidification, it's the right axis values that shows the amount of emission for the boxes, with the unit 10^{-6} kg CFC-eq for stratospheric ozone depletion and 10^{-2} kg SO_2-eq for acidification. The emissions from the GFRP-box is shown in whole lines, the emissions from the PE-box is shown with dashed lines.

The amounts of emissions from climate change and human toxicity are showed on the left axis, and the amounts from stratospheric ozone depletion and acidification are showed on the right axis, where the units for each impact category is marked. However, the amounts are not of that much interest in this figure, it is the relation between the PE-box and the GFRP-box over different lifetime that is most relevant

Looking at all the different lifetimes, a trend is seen for the GFRP-box's emissions when the lifetime of the PE-box increases (figure 18). If the lifetime of the PE-box is 26 years, which is the lowest lifetime value given by one of the sources, the impacts from the GFRP-box is 130% higher than the PE-box. If the lifetime of the PE-box is 100 years, the highest lifetime given by one of the sources, the impacts from the GFRP-box needs to be multiplied with 500% giving the PE-box 5 times as long lifetime. Last, a lifetime value of 75 years for the PE-box is used to get a value between the others. When the lifetime is 75 years, the PE-box has 375% longer lifetime than the GFRP-box. The impact values from the GFRP is multiplied with 375%, giving the values of the emissions from the GFRP-boxes produced and used over 75 years (table 9 & figure 18).

The trend is clear, the longer lifetime the PE-box has, the emissions from the GFRP-boxes are increased due to the increased number of boxes needed for the lifetime of one PE-box. An exponential growth is seen.

5.4.2 Dominance analysis

In a dominance analysis, you look at the processes or flows that has the greatest impact and from that evaluate how and where improvements can be made (Bauman et al., 2004). In this study, the greatest emissions from the GFRP-box came from the production of the polyester resin, the glass fibre production and the combustion. For the PE-box, the greatest emissions came from the production of PE-granulates, the combustion, the production of electricity, the production of aluminium and the transport. If you look at it from a process perspective, it is the production of the box that has the greatest impact for both boxes, followed by the combustion process.

Most of these flows are upstream processes, which means that they can be hard to affect directly. One thing that can be done is to use higher amount of recycled material, which will reduce the emissions from the production process, since less raw material is used. However, this is only possible for the PE-box material. For the GFRP-box, it could instead be evaluated if other types of plastics can be used instead of the non-recyclable polyester resin which is a thermoset plastic. If a thermoplastic that can be recycled would be used instead, the emissions would be reduced greatly. Alternative material for glass fibre could be evaluated as well, possibly a material that has lower emissions in the production but also that are more merciful to use.

Another improvement could be to put demands on the electricity production by choosing an electricity contract that only includes electricity from renewable sources. Other, the emissions from the combustion process are very hard to affect, and as showed in the system expansion, the energy produced is better from a climate change perspective compared to the alternative. In the incineration plants, they already have multiple cleaning steps to reduce the emissions, which they improve every year with new research on the subject. Last, the transport can be both hard and easily affected. The transports from the production is easy to affect since it is the production company that decides upon these. By choosing alternative fuels, such as HVO, the emissions can be reduced by some amounts. Also, planning the transport in a sufficient way, with deliveries to multiple customers at the same time, and by using the truck for other purposes on the way back, the emissions could be reduced. The transports that are harder to affect are the ones to the waste management, since these are decided by the users, and the transports of raw material. The raw material transport can be affected in some ways by putting demands on the suppliers.

6. Discussion

Polyethylene vs glass fibre reinforced plastic

In all the simulations and scenarios done for the two boxes, it is clear that the GFRP-box has much higher impact on all of the impact categories compared with the PE-box. The single biggest factor why the emissions from the GFRP-box is so much higher than the ones from the PE-box is the production of the polyester resin used. This flow has been showed to contribute with more than 70% of the emissions for all the impact categories. However, it is important to emphasize that the data on the polyester resin production comes from *Ecoinvent* and is not directly applied to this example. There can be many parts that differs for the specific resin used in the production of the boxes to the ones used in *Ecoinvent*. But it does show upon the difference in emissions between different type of plastics, and how important it is to choose plastics from producers that work with reducing these emissions.

One other important factor for the large difference in impact between the two boxes is their different lifetime, where the PE-box has as much as 225% longer lifetime than the GFRP-box. However, even when the lifetime is not accounted for, the GFRP-box has still larger impact than the PE-box as discussed above, but the lifetime still is a very important factor to consider here.

Another reason for the high emissions from the GFRP-box is the higher amount of material used. One GFRP-box weights 35 kg, where 26 kg is polyester, 7 kg glass fibre and 2 kg iron hinges. The PE-box however, weight only 23,66 kg where 23,5 kg is polyethylene and 0,16 kg is aluminium hinges. So, since the demand for raw-material is larger for the GFRP-box, the emissions becomes larger as well. But even though the GFRP-box weights more and demands more raw-material, the emissions would still be much higher than for the PE-box if the amount of raw-material would be the same.

Last, the issue of not being able to recycle the GFRP-box adds to the negative aspects of it since it was showed for the PE-box that the emissions can be substantially reduced by recycling. This would especially be the case if the plastic in the GFRP-box could be recycled, since the emissions mostly comes from producing virgin polyester and recycling would remove most of this. Furthermore, the lower energy value and the amount of ash/unburn material makes the combustion of the GFRP-box not as profitable as the PE-box and the savings from produced heat and electricity becomes lower.

Largest contributors to the impacts and how to reduce them

In the overall impact from the PE-box, it is the production of the box that has the highest impact when looking at WS1. For climate change and acidification, it is the production of virgin PE-granulates that contributes to most of the GHG emitted. Since this is an upstream process it is quite hard to minimize these impacts directly. What can be done is to use more recycled PE-granulates and to put demands on the producer of the granulates that they use more recycled material in their products. One important thing to do as the provider of a product is to inform the costumers about the recycling possibilities of the product and how they do this in the most efficient way. Here it is important to inform that the hinges need to be removed before recycling the box. This to make sure that the plastic can be recycled without any contaminations, and so that the aluminium also is recycled in the right way.

For human toxicity, the aluminium production is a large emission factor. This is also an upstream process that can't be address straight on. The solution is the same as for the PE-granulates, to make sure that more recycled material is used and to put demands on the producers to use larger quantities of recycled material. Another large contribution of emissions for human toxicity is the electricity used. The electricity is also a large source of emissions for stratospheric ozone depletion and smaller amount for acidification. The production of electricity is an upstream process that easily can be addressed by changing the origin of the electricity. The production company that produced the boxes uses today the Nordic residual electricity mix that contains 43% fossil energy, 41% nuclear energy and 17% renewable energy. By changing the electricity to 100% renewable energy, which can be made for most of the electricity companies, the emissions will decrease greatly, making the impacts on stratospheric ozone, human toxicity and acidification much lower.

The styrene emissions from the polyester resin used in the GFRP-box does not have a large impact in human toxicity according to the LCIA. This since the emissions are small compared to other emissions causing an impact on human toxicity. But non-the less, it is important to address the issue styrene bring for the workers exposed to the fumes. As mentioned earlier, it can have effects such as depression, slower reactions and cancer. Therefore, one should have in mind these negative aspects connected to the GFRP-boxes' production. Another emission from the GFRP-box that does not show in the LCIA impact on human toxicity is the glass fibre particles release from both production, use phase and waste management. These emissions are very hard to quantify; therefore, they don't show an impact. But the issues with dermatitis, lung problems and in some cases cancer needs to be considered in the overall estimation of the box.

Transportation is not a large contributor to the total impact from the PE-box lifecycle, but this does not make it less important to consider. The impacts are quite large for stratospheric ozone depletion, human toxicity and acidification. Transport is both easy and hard to change. For the transport from and to the production, demands can be put on the company providing the transport service. Also, if the transport is planned in a sufficient way, with deliveries to multiple customers at the same time together with transport of other goods on the way back, the emissions from the transportation could be reduced. Today there are many alternatives to diesel for the trucks, where one of the most common one is HVO-diesel, which can be used in all trucks. HVO is a synthetic diesel made from plant and animal waste, mostly from offal (Energifabriken, n.y). HVO is 100% renewable, free from sulphur and aromatics, generates less cold start emissions and emits between 50-90% less CO_2 depending on what type of waste it is produce from (ibid; OK-Q8 AB, 2017). There can be up to 33% less emissions of particles, 9% less NO_x, 30% less HC and 24% less CO emissions by using HVO-diesel instead of the traditional diesel (Energifabriken, n.y). The transports that are harder to regulate are first, the ones from the user to the waste management. There are too many different users to be able to influence their way of transporting the waste. Another transport that are almost impossible to influence are the one upstream the production of PE-granulates. The transport in the waste management are also quite hard to affect, however, the companies probably already has an internal ongoing environmental work and therefore the transports are already minimizing their emissions.

Last, the combustion of the box generates a lot of GHG-emissions, giving a large impact on climate change. These emissions are hard to change from the company's point of view, since they can't make sure that the boxes are recycled to 100%. However, to inform customers about the importance of recycling and how to do this, there could be a large reducing in the amount being combusted. For the waste produced in the production part, these are already recycled to 100%. The combustion itself is impossible to affect from a company's point of view. The waste-to-energy plants are improving every year with different adjustments that reduced the emissions produced. Also, the positive outcome of the combustion, where energy is produced, cannot be forgotten, as shown in the system expansion. The energy produced can be seen as a replacement for another energy source that produces more emissions, for example natural gas, and therefore the combustion reduces the overall emissions.

The different waste scenarios

When comparing the different waste scenarios for the PE-box, it is quite clear that the recycling (WS3) is the best scenario for all but one of the impact categories. For climate change, acidification and human toxicity, the differences in emissions between WS1 and WS2 (with large amount of combustion) and WS3 (100% recycling) is quite substitutional with over 50% reduction in emissions (figure 15). For stratospheric ozone depletion however, the emissions from WS3 is a bit larger than for the other two scenarios, this because of the transport where the distance to the recycling plant is longer than to the combustion plant.

For the GFRP-box, the emissions are very similar for all the waste management scenarios. A smaller difference is seen for climate change where the landfill has lower emissions compared to the other two (figure 16). Landfill as a process has very low emissions, whereas combustion has quite large emissions of GHG contributing to impact on climate change. Therefore, landfill looks like the better option compared to combustion. What is not assessed are the positive output of energy produced in the combustion process. The energy produced can replace energy from other energy sources that has higher emissions, and therefore the emissions from the combustion need to be addressed accordingly. Furthermore, waste put on landfill is an issue of area, where the waste is put in a pile, and nothing is done to it. If all waste would be put on landfill, it would take up a large portion of land that could be used for something else, for example forest, which could work as a CO_2 sink, giving a reduction of CO_2. The boxes themselves does not contribute to much emissions on the landfill, but other type of waste produces many different emissions giving an impact on many of the impact categories. Landfill is not a sustainable waste management method and should be used for as small extent as possible.

Heat recovery in the production of the PE-box

In the production of the PE-box, there is a large heat loss from the oven. Almost no energy is recovered from the heat produced. The heat of the oven is around 300°C which contains a lot of energy that could be reused for district heating or transformed into electricity. The possibilities are many, and should be considered for the future production of the PE-box, to be able to reduce the environmental impact even more. Furthermore, not using that much amount of energy is a waste of resource, especially for a production of this size, since the benefits could be quite large with quite low effort.

Sensitivity analysis

The results from the sensitivity analysis emphasizes the results from the base case, where the lifetime is not included as a factor. The longer the lifetime of the PE-box is, the emissions from the GFRP-boxes are increased due to the increased number of boxes needed for the lifetime of one PE-box. For the scenario where the lifetime of the PE-box is put to 26 years, almost the same amount of years as the GFRP-boxes' lifetime, the emissions are still much larger for the GFRP-box. Comparing the scenario for 26 years lifetime with the 100-year lifetime scenario, the emissions are increased by almost 400%, showing the importance of including the products lifetime and how much the emissions can be reduced by having a product with long lifetime. This fact should be of high importance when buying a product, any product, since the lifetime for many products have a large impact on environmental impacts. By using a box with long lifetime, the emissions can be reduced by 500%.

Inventory analysis

Sometimes it is possible to make conclusions directly in the inventory analysis, where the results from the LCIA could be quite clear. However, in this study this could not be done completely, only some parts the results could be estimated. The lifetime of the boxes was assumed to have a large impact on the total emission of the boxes, exactly how much was hard to say, but since many of the sources showed upon a shorter lifetime of the GFRP-box, the trend was expected to be quite clear.

Looking at the different amount of raw material going into the processes, it was assumed that this would have some impact in the results, since most of the emissions was estimated to come from the production of raw material. However, the size of the emissions from the polyester resin used in the GFRP-box was never assumed to give such large impact as it did. Furthermore, the impacts from the emissions from the other raw materials could never have been estimated to have the different impacts as it did in the LCIA, therefore, one could with certainty say that the LCIA was a necessary step to show upon the impacts on the different impact categories.

From the inventory, I would have guessed that the impact on human toxicity would have been greater from the emissions of styrene and glass fibres, but as It turned out, these emissions was very small compared to other emissions giving an impact on human toxicity, that these ones was not even noticeable.

Sources of error and credibility of the results

There are no specific number on the lifetime of the boxes since it varies a lot depending on how it is being used and where it is located. Therefore, the lifetime can only be estimated, which several different sources have been asked to do. The sources consist of different experts on the type of material used (polyethylene and plastic composites) and users of the different boxes. A mean value has been calculated from their estimation to be used as a "base" case for the different boxes lifetime. Since the values used are only estimations from different people with different background, the numbers vary a lot and needs to be taken lightly, there are large sources of error here.

Another source of error that has been brought up earlier in the report is the data used from *Ecoinvent*. The data used is hard to trace and therefore it is difficult to know exactly what the data comes from and how it is estimated. Some data is specific to Sweden, while some data is estimated for Europe and the rest of the world. These bring a lot of error into the calculations since the data is not specified for the street sandboxes investigated.

Other data used in the calculations comes from a various number of sources, from different parts of the world and from a large span of years. For as much of the data as possible, data regarding Sweden has been used. If data for Sweden has not been available, data for the Nordic countries has been used at first, followed by data for Europe and last the rest of the world. This is an issue since many processes and emissions look very different depending on where in the world you are. For the publication year of the data, as resent data as possible has been used, however in some cases the newest data found has been from the 70's and 90's, where this data has been used in lack of other options. This brings some source of error since it for many processes has been a large effectiveness and reduction of many emissions in the last 20 years. All the data used has been collected from legit sources, either publications in large scientific journals, by authorities, from published books and by sources that has good knowledge in the area and are trust worthy. Some information and data has been collected personally from people in the business of producing the different boxes, from scientist at various locations and from other people that has good knowledge about the different processes addressed.

In this study, the recycling is set as a closed-loop, where all the recycled material goes back into the production of the box. In the actual production, this is not the case, both since there is not 100% effectiveness in a recycling facility, and in the production of the box there is no recycled material used today. This brings upon some misleading results for the waste scenarios including recycling as a waste management method, especially for the savings showed. However, the scenario is displayed in this study to show upon the possibilities of savings from using recycled material, to give the production company options on how they can reduce their emissions.

It can be argued if the results are trustworthy or not, due to the fact that the study has been made for a specific company that produced one of the boxes investigated, and therefore the results should be questioned if they are angled or not. To answer that, the study has been conducted by an outside resource, that has no connection to the company other than to present them with the results and to collect data on the product. The study has been made as a master thesis project, which means that the method and calculations has been overlook by a member of the University to make sure that the data collected has been treated in the same way. Since data on the upstream processes for both boxes have been collected from the same database, the results from the impacts calculated are trustworthy. One thing that can have altered with the results are the data on the production of the GFRP-box. Most of the data was collected from a company that produces that type of boxes, however, some data was not given and other more general sources was therefore used. However, these data make out a very small part of the study and should therefore not make a larger impact on the end results.

To sum it up, the study is credible when looking at the angling of the results for the company. However, the credibility of the results in general can be discussed, since some of the data are not specific for the material or process used, but instead is collected from other similar material or processes or from general data in databases.

Further studies and suggestions on improvement

This study has contributed with several different aspects that hasn't been addressed regarding a street sandbox. For example, it has showed that the raw material used are of high importance for all environmental aspects, together with the difference in lifetime, making the decision of what box to use from a sustainable point of view quite easy. However, the study is the only one of its kind and only two type of street sandboxes are addressed. There could be many other options to choose from which are not addressed here, where there could be a box that are better to choose from a sustainable point of view. The results are however highly relevant for both users, such as municipalities, and producers. It will provide them with many different information, giving them the possibility to make well-founded decisions regarding the sustainability for street sandboxes.

Further studies in the subject could be to make a similar LCA, but to use more original data directly connected to the actual processes, especially for the production of raw material where the sources of errors are assumed to be large since the processes are not adjusted for Sweden and the specific material used. This change will most likely decrease the emissions in some parts.

It could also be interesting to look more into the heat losses from the production of the PE-box. The energy loss is very large and should be considered to be recovered in different ways. An investigation should be done for the heat losses, where the exact amount of energy loss is calculated and different methods to recover the energy should be presented. This will not only benefit the environment due to less impact from energy production, but also the production company could benefit since the costs for electricity and/or heat will go down depending on the recovery method.

Using other type of materials to produce a street sandbox would be of great interest. Starting with usage of another type of plastic in the GFRP-box, preferable a plastic that is recyclable. Another suggestion for alternative raw material is to use a bio-based plastic, which probably would reduce many of the impacts on the impacts categories in this study. However, other impacts on other impact categories could rise instead and therefore a study on bio-based material usage could be of interest.

Last, the recycling assessment could be addresses in a different way if the LCA would be conducted again. As described above, there is a closed-loop recycling used in the study, but the open-loop recycling should also be addresses since this is the case in the production of the PE-box today. Therefore, for future studies, an open-loop recycling could be interesting to look upon, to be able to compare the different scenarios and discuss the different saving that can be done for each method respectively.

Personal reflections

The most surprising result for me would have to be the size of the impact from the production of the polyester resin used in the production of GFRP-box. I would have guessed that the impact from that production would be more similar to the production of the polyethylene granulates, but as it turned out the difference was huge.

Another wake up call for me was the amount of plastic waste recycled today, I would have thought that the percentage would have been much higher than 26%. Talking to different experts in the area, their answers where quite devastating, where they said that plastic that was contaminated with other materials was usually sent for incineration. This due to the fact that the cost to separate the materials where to high and that the market for recycled materials was too low to be able to get a profit from the recycled material.

Last, as I was talking a bit about earlier, I could never have thought that the difference in total impact from the boxes would have been as large as it turned out to be. In none of the impact categories or scenarios did the GFRP-box have lower impact than the PE-box.

7. Conclusion

The overall results of the LCA show that the PE-box has lower impact on all the impact categories compared to the GFRP-box, where the largest differences were found for human toxicity and stratospheric ozone depletion. Climate change was the impact category where the impact from the two boxes where closest. However, the GFRP-box had around 60% higher emissions than the PR-box (for the base scenario), making the difference large in this category as well. Recycling where shown to have a large positive feedback on the impacts, where the emissions from production decreased due to no input of raw material, which was the inputs showing large impact on many of the impact categories. Furthermore, the emissions form the recycling process was lower than the emissions from the combustion process, reducing the impact more. The impacts from the landfill scenario was a bit lower compared to the combustion, however, the combustion scenario is still a better option from a sustainable point of view, due to the positive feedback from the energy produced and the negative aspects of landfill. The lifetime of the boxes is of high importance when comparing the emissions with each other. Since the PE-box has more than double the lifetime of the GFRP-box, the impact of the GFRP-box will more than double since a box with a longer lifetime has a lower material requirement over time and therefore the emissions become lower.

Further studies should be done on other type of materials to produce the same box, where possibilities of for example bio-based plastics could be an option. Also, a similar study could be done, with the difference of using more primary data instead of general data, together with more data on the upstream processes, to get more reliable results. Furthermore, calculations should be done on an open-loop recycling together with a more accurate recycling rate than the once used here. As mentioned in the introduction, the usage of street sandboxes has been reduced the last couple of years, which brings up the question, are there other better alternatives for road maintenance in the winter time, that could replace street sandboxes? A LCA could be done where different maintenance alternatives are evaluated, to see which ones that are the better alternatives when looking at their complete lifecycle.

For the users of these type of sandboxes, for example the municipalities, housing complex and other authorities, the lifetime of the different type of material used in boxes, together with recycling possibilities, should be a part of the requirements when purchasing new boxes. As shown in this study, these factors have a large impact on the environmental impact categories, and should therefore be included in purchasing procedures to contribute to a more sustainable society.

The PE-box has lower impacts on all the impact categories compared to the GFRP-box. This due to the longer lifetime, the recycling possibilities, the lower amount of raw material needed, the lower impacts from the production of raw material and the higher heat value leading to more energy produced from combustion.

References

A. Schulman (2015). *ICORENE – Powders for Rotomoulding.* [Brochure] Available: http://www.aschulman.com/Documents.aspx?ID=133 [2017-03-06].

AlMa'adeed, M., Ozerkan, G., Kahraman, R., Rajendran, S. & Hodzic, A. (2011). Life Cycle Assessment of Particulate Recycled Low Density Polyethylene and Recycles Polypropylene Reinforced with Talc and Fiberglass. *Key Engineering Materials*, vols. 271-272, pp.999-1004. DOI: 10.4028/www.scientific.net/KEM.471-472.999.

AQMD – South Coast Air Quality Management District (2015). *Guidelines for Calculating Emissions from Polyester Resin Operations*. California: South Coast AQMD.

Baumann, H. & Tillman, A-M. (2004). *The Hitch Hiker's Guide to LCA – An orientation in life cycle assessment methodology and application*. Lund: Studentlitteratur AB.

Bolur, P.C. (2007). *A Guide to Injection Moulding of Plastics, 3rd edition*. Available: http://www.pitfallsinmolding.com/energyeffic1.html [2017-05-31].

CIEC Promoting Science at the University of York (2014). *Poly(ethene) (Polyethylene).* Available: http://www.essentialchemicalindustry.org/polymers/polyethene.html [2017-03-06].

Damgaard, A., Larsen, A.W. & Christensen, T.H. (2009). Recycling of metals: accounting of greenhouse gases and global warming contributions. *Waste Management & Research*, issue 27, pp. 773-780.

Eastes, W. & Hadley, J.G. (1996). A Mathematical Model of fiber Carcinogenicity and Fibrosis in Inhalation and Intraperitoneal Experiments in Rats. *Inhalation Toxicity – International Forum for Respiratory Research*, issue 8(4), pp. 323-343.

Emil Deiss KG (2017). *Grundläggande om polyetylen – PE.* Available: https://www.deiss.de/se.php/mehr/polyethylen.html [2017-03-02].

Energifabriken (n.y). *HVO – bättre än diesel i alla fordon.* Linköping: Energifabriken. [Product data sheet]. Available: https://www.energifabriken.se/files/files/Produktblad_HVO.pdf [2017-05-30].

Fråne, A., Stenmarck, Å., Sörme, L., Carlsson, A. & Jensen C. (2012). *Kartläggning av plastavfallsströmmar i Sverige.* Norrköping: Sveriges Meteorologiska och Hydrologiska Institut (SMED, no 108 2012). Available: http://www.smed.se/wp-content/uploads/2012/08/Slutrapport4.pdf [2017-03-27].

Gode, J., Martinsson, F., Hagberg, L., Öman, A., Höglund, J & Palm, D. (2011). *Miljöfaktaboken 2011 – Uppskattade emissionsfaktorer för bränslen, el, värme och transporter*. Stockholm: Värmeforsk Service AB (Värmeforskrapport 1183).

Gontia, P. (2014). *Life cycle assessment of bio-based sodium poly-acrylate production from pulp mill side streams-Case at TMP and sulphite pulp mill.* Chalmers University of Technology. Department of Energy and Environment/ Industrial Ecology programme.

Groth-Marnat, G. (1993). Neuropsychological effects of styrene exposure: a review of current literature. *Preceptual and Motor Skills*, issue 77(3), pp. 1139-1149.

Hallabro Plast AB (2013). *Tillståndsansökan – För flyttning och utökning av befintlig verksamhet gällande Hallabro Plast AB. Kalmar: Länsstyrelsen.* Available: http://www.lansstyrelsen.se/kalmar/SiteCollectionDocuments/Sv/miljo-och-klimat/verksamheter-med-miljopaverkan/tillstandsprovning/P%C3%A5g%C3%A5ende%20tillst%C3%A5ndsans%C3%B6kningar/Hallabro%20plast%20AB/Ansokan%20Hallabro%20Plast%20AB%202013.pdf [2017-03-28].

Holstensson, J. & Häggström, M. (2016). *Utveckling av hyttmodul för fritidsbåt*. Högskolan i Skövde. Integrerad Produktutveckling (Examensarbete grundnivå, G2E 30 Högskolepoäng).

Johnson, T. (2017a). Introduction to vacuum infusion. *about.com*, n.d. Available: http://composite.about.com/od/Manufacturing/a/Introduction-To-Vacuum-Infusion.htm [2017-04-21].

Johnson, T. (2017b). Gel Coat Variables. *about.com*, n.d. Available: http://composite.about.com/od/databases/a/Gel-Coat-Variables.htm [2017-04-21].

Johnson, T. (2017c). Thermoplastic vs Thermoset Resins – The difference In Two Resins Used In FRP Composites. *about.com*, March 27. Available: https://www.thoughtco.com/thermoplastic-vs-thermoset-resins-820405 [2017-04-21].

Kampa, M. & Castanas, E. (2007). Human health effects of air pollution. *Environmental Pollution*, issue 151(2), pp. 362-367.

Karolinska Institutiutet (2015). *Små partiklar kan ge stor skada.* Available: http://ki.se/forskning/sma-partiklar-kan-ge-stor-skada [2017-03-17].

Keson, A. (2009). The Different Polyester Resins. *FiberglassBlog* [Blog]. 16th of February. Available: http://fiberglassblog.com/2009/02/16/the-different-polyester-resins/ [2017-04-20].

Länsstyrelsen – Blekinge län (2005). *VOC – lättflycktiga organiska ämnen (Volatile Organic Compounds).* Available: http://www.lansstyrelsen.se/blekinge/Sv/miljo-och-klimat/verksamheter-med-miljopaverkan/miljofarlig-verksamhet/Pages/voc-direktivet.aspx [2017-03-17].

Li, C-T., Zhuang, H-K., Hsieh, L-T., Lee, W-J. & Tsao, M-C. (2001). PAH emission from the incineration of three plstic wastes. *Environment International*, issue 27, pp. 61-67.

Lindgren, M. (2001). *Mijlöavgift på utsläpp av kväveoxider vid energiproduktion år 2000 – resultat och statistik.* Naturvårdsverket (713-4601-01 Rt). Available: https://www.naturvardsverket.se/upload/miljoarbete-i-samhallet/miljoarbete-i-sverige/energi/nox/nox-statistik-promemoria-2000.pdf [2017-05-03].

Lindgren, M. (2001). *Miljöavgift på utsläpp av kväveoxider vid energiproduktion år 2000 – resultat och statistik.* Stockholm: Naturvårdsverket - Miljörättsavdelningen – Tillsynsenheten (Promemoria: 712-4601-01 Rt).

McCreanor, J., Cullinan, P., Nieuwenhuijsen, M.J., Stewart-Evans, J., Malliarou, E., Jarup, L., Harrington, R., Svartengren, M., Han, I-K., Ohman-Strickland, P., Chung, K.F. & Zhang, J. (2007). Respiratory Effects of Exposure to Diesel Traffic in Persons with Asthma. *The New England Journal of Medicine,* issue 357 pp.2348-2358.

Molded Fiber Glass Companies (2013). *FactsAboutStyrene2013.* [Video] Available: https://vimeo.com/78076673 [2017-04-12].

Molded Fiber Glass Companies (2017). *Technical Design Guide for FRP Composite Products and Parts – Techniques & Technologies for Cost Effectiveness.* Available: http://www.moldedfiberglass.com/sites/default/files/docs/MFG_Technical_Design_Guide_FRP_Composite_0.pdf [2017-04-12].

Mølgaard, C. (1995). Envrionmental impacts by disposal of plastic from municipal solid waste. *Resources, Conservation and Recycling*, issue 16, pp. 51-63.

Nationalencyklodepin (2017). *Försurning.* Available: http://www.ne.se/uppslagsverk/encyklopedi/l%C3%A5ng/f%C3%B6rsurning [2017-03-14].

Naturvårdsverket (2016a). *Kväveoxidutsläpp.* Available: http://www.miljomal.se/Miljomalen/Alla-indikatorer/Indikatorsida/?iid=91&pl=1 [2017-03-16].

Naturvårdsverket (2016b). *Fakta om kolmonoxid i luft.* Available: http://www.naturvardsverket.se/Sa-mar-miljon/Klimat-och-luft/Luftfororeningar/Kolmonoxid/ [2017-03-17].

Naturvårdsverket (2016c). *Vägtrafikens miljöpåverkan.* Available: http://www.naturvardsverket.se/Miljoarbete-i-samhallet/Miljoarbete-i-Sverige/Uppdelat-efter-omrade/Transporter-och-trafik/Vagtrafik/Vagtrafikens-miljopaverkan/ [2017-03-17].

Naturvårdsverket (2016d). *Partiklar i luft.* Available: http://www.miljomal.se/Miljomalen/Alla-indikatorer/Indikatorsida/?iid=105&pl=1 [2017-03-17].

Naturvårdsverket (2017). *Miljöproblem vid deponering*. Available: http://www.naturvardsverket.se/Sa-mar-miljon/Mark/Deponier/ [2017-03-10].

Nilsson, P. - SÖRAB (2007). *Stockholmregionens Avfallsråd – Förbränning.* http://www.atervinningscentralen.se/web/page.aspx?refid=182 [2017-03-02].

OK-Q8 AB (2017). *Nya Diesel Bio HVO – vårt bästa miljöval.* Tillgänglig: https://www.okq8.se/pa-stationen/drivmedel/diesel/diesel-bio-hvo/ [2017-05-30].

Öresundskraft AB (2016). *Elens ursprung.* Available: https://oresundskraft.se/foeretag/produkter-tjaenster/elhandel/ursprungsmaerkning/ [2017-03-27].

OSHA (Occupational Safety and Health Administration) - United States Department of Labor (2005). *Fibrous Glass Dust*. Available: https://www.osha.gov/dts/chemicalsampling/data/CH_242120.html [2017-03-09].

Paulrud, S., Fridell, E., Stripple, H. & Gustafsson, T. (2010). *Uppdatering av klimatrelaterade emissionsfaktorer.* Norrköping: Sveriges Meterologiska och Hydrologiska Institut (SMED Rapport No 92 2010). Available: http://www.smed.se/wp-content/uploads/2012/01/Uppdatering-av-klimatrelaterade-emissionsfaktorer.pdf [2017-05-03].

Pettersson, C., Andreasson, S., Skrifvars, M. & Åkesson, D. (2009). *Jämförelse av befintliga återvinningsprocesser för kompositmaterial – en förstudie gällande mikrovågspyrolys*. Borås: Waste refinery (WR-22). Available: http://wasterefinery.se/media/2016/02/WR22_Slutrapport100302.pdf [2017-05-31].

Pickering, S.J. (2006). Recycling technologies for thermoset composite materials – current status. *Composites: Part A: applied science and manufacturing.* Part A 37, pp. 1206-1215.

Pleijel, H. (2007). *Transboundary Air Pollution – Scientific Understanding and Environmental Policy in Europe.* Ed. 1:1. Poland: Studentlitteratur.

PTO – Plastic Technology Composites (2013). *Om PTC.* Available: http://www.ptc.nu/index.php/om-ptc-composites [2017-03-08].

Queensland Government (2016). *Nitrogen oxides.* Available: https://www.qld.gov.au/environment/pollution/monitoring/air-pollution/nitrogen-oxides/ (2017-03-17].

Renova (2013). *From waste to clean energy – Sävenäs Waste-to-Energy Plant, Gothenburg.* Göteborg: Renova AB. [Brochure]. [2017-03-06].

Renova (2015). *Miljörapport 2015 – för avfallskraftvärmeverket och sorteringsanläggningen, inklusive återvinningscentralen och anläggningen för farligt avfall vid Sävenäs.* Göteborg: Renova AB (Dnr 0116/16).

RotationsPlast (n.y.a). *Metod – Rotationsgjutning*. http://www.rotationsplast.se/metod.html [2017-02-13].

RotationsPlast (n.y.b). *Metod – Metodens fördelar*. http://www.rotationsplast.se/metodensfordelar.html [2017-02-15].

Ruegger, M. (1996). Are artificial mineral fibers harmful to health and unsuitable for asbestos substitute?. *Praxis - Revue Suisse de medicine Praxis (fmr: Schweizerische Rundschau fur Medizin Praxis),* issue 85(33), pp. 961-966.

Rummukainen, M. (2005). *Växthuseffekten.* Norrköping: SMHI (Meteorologi no 119). Available: http://www.smhi.se/polopoly_fs/1.1795!meteorologi_119_webb%5B1%5D.pdf [2017-03-14].

Samuel, M. (2003). A new technique for recycling aluminium scrap. *Journal of Materials Processing Technology*. Issue 135, pp. 117-124.

Scottish Environment Protection Agency (n.y). *Scottish pollutant release inventory – Methane.* Available: http://apps.sepa.org.uk/spripa/Pages/SubstanceInformation.aspx?pid=65 (2017-03-17].

Sertoli, A., Francalanci. & Giorgini, S. (2000). Fiberglass Dermatitis. In: Kanerva, L., Wahlberg, J.E., Elsner, P. & Maibach, H.I. (ed), *Handbook of Occupational Dermatology*. Berlin Heidelberg: Springer-Verlag, pp. 122-134.

Sertoli, A., Giorgini, S. & Farli, M. (1992). Fiberglass Dermatitis. *Clinics in Dermatology,* issue 10(2), pp.167-174.

Shi, X. (2009). Winter road maintenance: Best practices, emerging challenges and research needs. *Journal of Public Works & Infrastructure*, issue 2(4), pp. 318-326.

Sjögren, A. (2010). Värt att veta om kompositer – En specialtidning om kompositer. *Plastforum,* issue 12(2). Available: http://zoomin.idt.mdh.se/course/ppu104/dokument/Kompositer_PF_1210.pdf [2017-03-08].

Skrifvars, M. & Åkesson, D. (2013). *Energi och material för hållbar utveckling – Återvinning av komposit 2008/0647.* Borås: Högskolan i Borås – Institutionen Ingenjörshögskolan (Dnr 918-08-62).

SMHI (2016). *Varför bryts ozonet ner?* Available: http://www.smhi.se/kunskapsbanken/meteorologi/varfor-bryts-ozonet-ner-1.3827 [2017-03-14].

Stanton, M.F., Layard, M., Tegeris, A., Miller, E., May, M. & Kent, E. (1977). Carcinogenicity of Fibrous Glass: Pleural Response in the Rat in Relation to Fiber Dimension. *Journal of the National Cancer Institute*, issue 58(3), pp. 587-603.

Stig, L. (2012). *Miljöbedömning Cefibra – Referensmiljöer för framtidens produkter*. Östersund: Jegrelius – Institutet för tillämpad grön kemi (Miljöbedömning Re8). Available: http://www.jegrelius.se/wp-content/uploads/2014/04/Miljobedomning-Re8.pdf [2017-03-14].

Svenska Tanso AB (n.y). *Vakuuminjicering*. Available: http://www.tanso.se/Vakuuminjicering.htm [2017-03-08].

Sveriges Lantbruksuniversitet, SLU (2016). *Vad är livscykelanalys?*. Available: https://www.slu.se/institutioner/energi-teknik/forskning/lca/vadar/ [2016-12-07].

Swerec (2015). *Swerec kommunplast / Swerec plastic bulky waste* [Video]. Available: https://www.youtube.com/watch?v=mnDp9APF0ik [2017-05-29].

Tillman, A-M., Baumann, H., Eriksson, E. & Rydberg, T. (1991). *Livscykelanalyser för förpackningsmaterial – beräkning av miljöbelastning.* Göteborg: Chalmers Industriteknik.

United Nations (n.y). *Some Ozone Depleting Substances in Different Industry Sectors.* Available: http://www.un.org/en/events/ozoneday/substances.shtml [2017-03-14].

Västia Plastindustri AB (n.y). *Dags att beställa gatusandlåda!*. Lilla Edet: Västia Plastindustri AB. [Bochure] Available: http://www.vastia.se/produkter/gata-fastighet [2017-03-10].

White, D.M., Daniell, W.E., Maxwell, J.K and Townes, B.D. (1990). Psychosis following styrene exposure: a case report of neuropsychological sequelae. *Journal of clinical and experimental neuropsychology*, issue 12(5), pp. 198-806.

Appendix

A – Results from calculations in openLCA

The results are for WS1, with 74% combustion and 26% recycling for the PE-box and 85% combustion and 15% landfill for the GFRP-box.

Polyethylene box

Climate change (GWP 100a)			
%	**%**	**Process**	**kg CO_2-eq**
100,0%		Use phase	104,18
50,3%		Combustion	52,36
	50,2%	*-Incineration process*	52,33
	0,03%	*-transport*	0,04
43,2%		Production PE-box	44,99
	35,1%	*-polyethylene production*	36,61
	4,9%	*-transport*	5,08
	2,1%	*-electricity*	2,21
	1,1%	*-aluminium production*	1,10
5,8%		Recycling PE	6,08
	5,5%	*-recycling process*	5,76
	0,3%	*-transport*	0,31
	0,0%	*-electricity*	0,004
0,7%		Transport	0,75
5,9%		Total transport	6,18
Stratospheric ozone depletion (steady state)			
%	**%**	**Process**	**10^{-6} kg CFC-11-eq**
100,00%		Use phase	4,55
95,5%		Production PE-box	4,35
	72,7%	*-electricity*	3,31
	20,4%	*-transport*	0,93
	2,1%	*-aluminium production*	0,10
	0,4%	*-polyethylene production*	0,02
3,0%		Transport	0,14
1,4%		Recycling PE	0,06
	1,2%	*-transport*	0,06
	0,1%	*-electricity*	0,006
0,07%		Combustion	0,003
	0,07%	*-transport*	0,003
24,7%		Total transport	1,12
Acidification (average European)			
%	**%**	**Process**	**10^{-2} kg SO_2-eq**
100%		Use phase	20,06
88,2%		Production PE-box	17,69
	69,1%	*-polyethylene production*	13,87

	8,5%	*-transport*	1,70
	5,8%	*-electricity*	1,16
	4,8%	*-aluminium production*	0,96
10,0%		Combustion	2,00
	9,9%	*-Incineration process*	1,99
	0,06%	*-transport*	0,01
1,3%		Transport	0,25
0,6%		Recycling PE	0,12
	0,5%	*-transport*	0,10
	0,01%	*-electricity*	0,002
10,3%		Total transport	2,07
Human toxicity (infinite)			
%	**%**	**Process**	**kg 1,4-DCB-eq**
100%		Use phase	23,38
97,1%		Production PE-box	22,71
	56,1%	*-aluminium production*	13,13
	20,1%	*-electricity*	4,71
	12,4%	*-transport*	2,90
	8,4%	*-polyethylene production*	1,97
1,8%		Transport	0,43
0,8%		Recycling PE	0,19
	0,8%	*-transport*	0,18
	0,04%	*-electricity*	0,009
0,2%		Combustion	0,06
	0,2%	*-Incineration process*	0,04
	0,1%	*-transport*	0,02
15,08%		Total transport	3,53

Glass fibre reinforced plastic box

Climate change (GWP 100a)			
%	%	Process	kg CO_2-eq
100,00%		Use phase	256,03
88,67%		Vacuum injection	227,03
	78,98%	*-polyester resin production*	202,20
	7,08%	*-glass fibre production*	18,12
	1,95%	*-transport*	4,98
	0,42%	*-iron production*	1,08
	0,25%	*-electricity*	0,65
10,89%		Combustion	27,88
	10,86%	*-incineration process*	27,82
	0,02%	*-transport*	0,06
0,43%		Transport	1,11
0,004%		Landfill	0,01
	0,003%	*-transport*	0,008
	0,001%	*-diesel*	0,003
	0,000%	*-electricity*	0,00003
2,41%		Total transport	6,16
Stratospheric ozone depletion (steady state)			
%	**%**	**Process**	**10^{-6} kg CFC-11-eq**
100%		Use phase	23,80
99,11%		Vacuum injection	23,58
	82,18%	*-polyester resin production*	19,56
	8,71%	*-glass fibre production*	2,07
	4,10%	*-electricity*	0,98
	3,82%	*-transport*	0,91
	0,30%	*-iron production*	0,07
0,85%		Transport	0,20
0,02%		Combustion	0,005
	0,02%	*-transport*	0,005
0,02%		Landfill	0,005
	0,013%	*-diesel*	0,003
	0,006%	*-transport*	0,002
	0,0002%	*-electricity*	0,0001
4,69%		Total transport	1,12
Acidification (average European)			
%	**%**	**Process**	**10^{-2} kg SO_2-eq**
100,00%		Use phase	85,00
97,48%		Vacuum injection	82,85
	81,45%	*-polyester resin production*	69,23
	13,03%	*-glass fibre production*	11,07
	1,97%	*-transport*	1,67
	0,63%	*-iron production*	0,54

	0,40%	*-electricity*	0,342
2,08%		Combustion	1,77
	2,06%	*-incineration process*	1,75
	0,02%	*-transport*	0,02
0,44%		Transport	0,37
0,01%		Landfill	0,005
	0,003%	*-transport*	0,003
	0,003%	*-diesel*	0,002
	0,00002%	*-electricity*	0,00002
2,43%		Total transport	2,07
Human toxicity (infinite)			
%	**%**	**Process**	**kg 1,4-DCB-eq**
100,00%		Use phase	285,86
99,76%		Vacuum injection	285,16
	73,46%	*-polyester resin production*	210,00
	24,05%	*-glass fibre production*	68,74
	1,00%	*-transport*	2,85
	0,76%	*-iron production*	2,18
	0,49%	*-electricity*	1,39
0,22%		Transport	0,63
0,02%		Combustion	0,06
	0,01%	*-incineration process*	0,03
	0,01%	*-transport*	0,03
0,002%		Landfill	0,006
	0,002%	*-transport*	0,005
	0,0005%	*-diesel*	0,001
	0,00003%	*-electricity*	0,0001
1,23%		Total transport	3,52

B – Data for calculations on emissions

Emissions from combustion (100%)

	Heat value (MJ/kg)	**Emission factor CO_2** (kg/MJ)	**Emission factor NO_x** (kg/MJ)[5]	**CO_2** (kg/kg)	**CO_2** (kg/box)	**NO_x** (kg/kg)	**NO_x** (kg/box)	**Dust** (kg/kg)	**Dust** (kg/box)	**Ash** (g/kg)	**Ash** (kg/box)
PE-box											
LDPE	43[6]	0,07[7]	0,00005	3,01	70,7	0,002	0,0536	0,000002[8]	0,00004	15[9]	0,35
Al	30,6[6]	-		-	-	0,002	0,0003	0,000760[6]	0,00012	1899[6]	0,30
Total					70,7		0,0538				0,66
GFRP-box											
Glass fibre composite	23,6[10]	0,04[11]	0,00005	0,99	32,8	0,001	0,0413	0,000002[8]	0,00006	-	-
Iron	0[6]	-		-	-	-	-	-	-	1000	2
Polyester[12]	-	-		-	-	-	-	-	-	1000	7
Glass fibre12[12]	-	-		-	-	-	-	-	-	20	0,52
Total					32,8		0,04134		0,00006		9,52

[5] Lindgren (2001). *The data is the average emission of NO_x from waste-to-energy plants in Sweden.*
[6] Tillman et al. (1991)
[7] Paulrud et al. 2010)
[8] Renova (2015)
[9] Li et al. (2001)
[10] Pettersson et al. (2009)
[11] Gode et al. (2011)
[12] Table Z.

Emissions from recycling (100%)

	CO_2 (kg/kg)	CO_2 (kg/box)	CO (kg/kg)	CO (kg/box)	CH_4 (kg/kg)	CH_4 (kg/box)	N_2O (kg/kg)	N_2O (kg/box)	HC (kg/kg)	HC (kg/box)
Polyethylene[13]	0,942	22,137	0,0002	0,005	0,00002	0,0004	0,00006	0,001	6950	0,16
Aluminium[14]	0,007	0,001	-	-	-	-	-	-	-	-
Total		22,138		0,005		0,0004		0,001		0,16

Assumptions combustion of GFRP

	%	g/kg
Combustible polyester	98	980
Ash polyester	2	20
Ash glass fibre	100	1000
Ash iron hinges	100	1000

Table Z. Values of the percentage of material being combusted and the ash produced. These values are assumptions made with ground in the values from combustion of HDPE and with support from information by Research Engineer at Swerea SICOMP M. Juntikka, personal contact, March 22nd, 2017.

[13] Mølgaard (1995)
[14] Damgaard et al. (2009)