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Circular packaging plastic usage at construction sites

A study to increase the circularity of packaging plastic at construction sites in Sweden

Master's thesis in Industrial Ecology

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: The image is showing plastic packaging waste that are present at construction sites, Schoonderwalt M.K, (2019) Pexel, https://www.pexels.com/photo/plastic-waste-of-empty-containers-and-jars-5505698/

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Abstract

In 2017 there were 349 000 000 tonnes of plastics produced worldwide (Plastics Europe, 2022) and 2 411 000 tonnes of plastics were produced and imported in Sweden, with the packaging industry being the single most user of plastic followed by the construction sector (Almasai et al., 2019). Of the total waste sent to incineration almost half of the waste was from packaging plastic (Almasai et al., 2019).
The aim of the project was to develop circular strategies that promote efficient plastic packaging usage at construction sites. The first step was to identify the total quantity and type of packaging plastic used and to quantify its presence in waste containers at the construction sites by using Material Flow Analysis (MFA). From the results, it was observed that Polyethylene (PE) was the major plastic type present at construction sites and the combustible containers had the highest quantities of plastic. Due to unreliable data, a worst case and a best case scenario were made with total recyclability of 5.8% and 40% respectively. An Life Cycle Analysis (LCA) was performed with the results obtained from MFA to create a baseline scenario that was used for formulating circular strategies. A total of 25 circular strategies were developed from seven design principles adapted to circular economy.
The suitable circular strategies were selected by a two step screening process which included environmental impacts and relevant framework. From the results, it could be observed that circular strategies with an emphasis on improving sorting and recycling, lowers the environmental impacts more than other strategies i.e transportation strategies. The circular strategy Less plastic types had the least amount of environmental impacts. This was due to the increased recyclability to 90%, which was achieved through improved sorting. This was accomplished by switching all hard plastic to the same type of Polypropylene (PP). An additional recycling scenario of 50% was considered because achieving a 90% recycling target might be difficult in the real world, given different working conditions at different construction sites. The results showed that even reaching a 50% recycling rate has significantly lesser impacts than the current scenario.
Since PE was the major plastic type observed at the construction sites, it could be easier for suppliers to shift all hard plastic to PE instead of PP. Therefore the recycling scenarios were tested with PE and the results showed that the environmental impacts were close to PP.

Keywords: Packaging Plastic, Construction site, Circular economy, MFA, LCA, Waste management

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Lastly, we express our gratitude to all the professors, classmates and friends who has supported us throughout our studies.
Thank you!

Adam Stemberger & Vinod Sai Pothireddy Gothenburg, May, 2022

List of Acronyms

Below is a table of acronyms used in the report.

BAU	Business as usual
CML	Centre of Environmental Science
COD	Chemical oxygen demand
EPS	Expanded polystyrene
GWP	Global warming potential
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LDPE	Low-density polyethylene
LEED	Leadership in Energy and Environmental Design
HDPE	High density polyethylene
MFA	Material flow analysis
PE	Polyethylene
PET	Polyethylene terephthalate
PEX	Cross-linked polyethylene
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
RER	Europe

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1 Introduction

With the total world population projected to rise to 9.7 billion by 2050 (United Nations, 2019), fulfilling the needs of all the people without depleting the earth's natural resources will be a big challenge. The use of fossil fuels like coal, natural gas, and oil are responsible for climate change causing various externalities across climate, environment, and health. Plastic production is responsible for causing negative impacts to the environment and human health and it is estimated that the greenhouse gas emissions from the plastic industry will surpass the coal fired power plants by 2030 (Bertrand, 2021).

The single use plastics of Polyethylene Tetrephthalate (PET), High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE), Polystyrene (PS), Polypropylene (PP),Polyvinyl Chloride (PVC), and Expanded Polystyrene (EPS) which are used for various packaging solutions are commonly used in today's society. Packaging plastic waste accounted for 47% of total plastic waste generated, with the USA as the highest generator of packaging plastic per capita. Different negative environmental impacts and negative effects on human health are caused by end-of-life treatment of plastic waste. Toxic gases released from burning plastic waste in open pits and the transfer of plastic to humans through the food chain from consumption of seafood are procedures that cause negative effects (United Nations Environment Programme, 2018).

In 2017 it is estimated that 349 000 000 tonnes of plastic were produced worldwide (Plastics Europe, 2022). In Sweden alone, 2 411 000 tonnes of plastic were produced and imported and 1 258 000 tonnes of plastic was used in the country. The packaging plastic industry is the single highest user of plastics, followed by the construction sector with 21% of the total plastic usage in Sweden, as seen in Figure 1.1 which shows plastic flows in Sweden.

Plastic waste comes from various sources in the construction sector. It can be from renovation, demolitions, and construction of new buildings. Packaging plastic is the highest percentage of plastic waste present in the combustible waste that comes from the construction sector as seen in the Figure 1.2.

With the increased usage of plastics comes increased quantities of plastic waste. There are 60 000 tonnes of plastic in sorted plastic waste. Approximations have shown that 89 000 tonnes from the construction sector are sent to incineration. This means that 149 000 tonnes of plastic waste are generated each year from the construction sector in Sweden. Only a small amount of this plastic waste is material recycled, about 0.8% (Almasai et al., 2019).

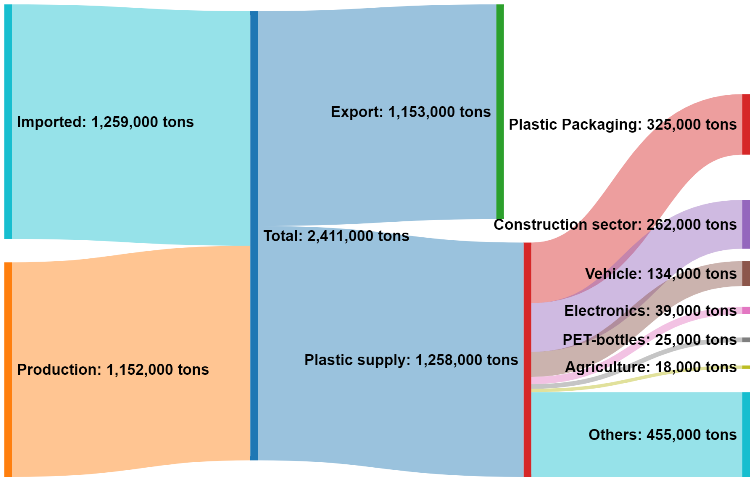


Figure 1.1: Plastic flows in Sweden 2016/2017 (Almasai et al., 2019).

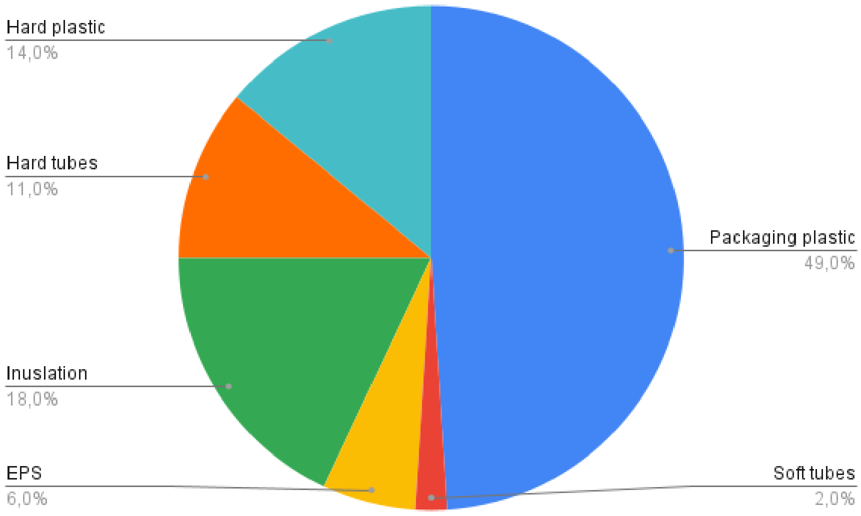


Figure 1.2: Plastic shares in incineration waste (Ahlm et al., 2021).

1.1 Aim

The aim of the project is to develop circular strategies for efficient plastic packaging usage in the construction sector in Sweden.

1.2 Research Questions

The following research questions were used to guide the project to reach the aim.

1. What are the types and quantities of packaging plastics used and what is the waste handling process for these, at a specific construction company?
2. Which circular economy strategies can be used to increase circularity for plastic packaging in the construction sector?

3. What are the environmental impacts associated with implementing the chosen circular strategies at the construction company?

1.3 Scope and Limitations

The scope is considered to be all new buildings and renovations of buildings for the construction company irrespective of their type and the stage of construction across Sweden. Some of the limitations in this report are that only new construction sites and renovations are considered hence the presence of packaging plastics at demolition sites are not considered. Only packaging plastic is quantified, the plastic used in building products i.e pipes, insulation, furnishings, etc are not taken into account. Therefore demolition sites are not taken into consideration due to low packaging plastic shares. Packaging products of only the types PP, PS, LDPE and PE are taken into account. HDPE is not considered a plastic type of its own.

2
Background

Plastic is widely used in Sweden and the construction sector. To reach the project goal it is essential to know what type of plastics exist, their environmental impacts, and methods to make the sector more circular.

2.1 Introduction to Plastics

Plastic is a polymeric material that can be shaped and molded into desired shapes with the application of pressure and heat (Rodriguez, 2021). The word polymer comes from the Greek words poly which means many and meros which means units (Science History Institute, n.d.). Polymers are chemical compounds that consist of many monomers linked together in long chain-like structures. Carbon and hydrogen are the elements that occur in most plastic polymers followed by oxygen, chlorine, fluorine found in polymers of different chemicals, and physical properties (Sidharthan and Westerlund, 2019).
Different properties of plastics depend on how the polymer structures are influenced. Properties can be added or removed by adding additional materials to the existing polymer structures, hence giving us different plastics with unique properties. Plastics can be divided into two major classifications thermoplastics and thermosets. Thermoplastics can be molded many times increasing their reusability, examples include PE and PS. Thermosets cannot be reused because they form rigid inseparable links during the initial chemical reaction (Rodriguez, 2021). These basic properties can be further changed or enhanced by adding additives such as plasticizers, colorants, stabilizers, and reinforcements (Rodriguez, 2021). Some of the most well-known resins which are majorly seen in the packaging industry are PE, PET, PP, PVC, and PS (Science History Institute, n.d.).

2.2 Production of plastic

Plastics are derived from fossil based or bio-based sources. Fossil based sources include coal, oil, natural gas, and bio-based sources include vegetable fats and oils, carbohydrates, and starch (Baheti, n.d.). In the following paragraph different steps in the production process are explained and illustrated in Figure 2.1.

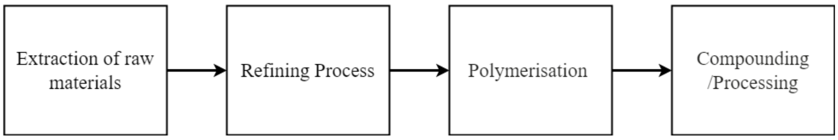


Figure 2.1: Plastic production processes

- Raw material extraction - The process begins with the extraction of required raw materials which are then sent to the refineries. Crude oil is pumped from the underground and loaded into tankers which will deliver it to refineries.
- Refining process - Crude oil is a complex mixture of many substances and must be refined before it can be put to use. In the oil refineries, crude oil undergoes distillation where it is heated in a furnace and the resulting vapour is sent to the fractional distillation column, where different materials are extracted at different temperatures. Among these materials the one which is important for plastic production is naphtha. However, naphtha is not useful at this stage as it is a complex hydrocarbon which needs to be cracked into simpler hydrocarbons (monomers) for example propane and ethane, which can be used to make different plastics (Baheti, n.d.).
- Polymerisation - Hydrocarbon monomers from the previous process will undergo chemical polymerisation to form long repeating thick viscous resins that can be used to make plastic products. There are two types of polymerisation. The first is addition polymerisation which includes introducing a catalyst and causing monomers to attach to the other and so on forming a long chain and the second is condensation polymerisation during which two monomers combine and form a dimer along with a by-product, the dimers then form tetramers to long polymers. Usually, the by-product is water which is removed and recycled (Baheti, n.d.).
- Compounding - The resins mixed with various additives colour pigments, flame retardants, fillers, lubricants, reinforcements, stabilisers etc will be sent to extruders where the polymer passes through a heated barrel with frictional forces. The resins will be homogeneously mixed and kneaded together making it plasticised. The pellets formed from this process can be moulded into various plastic products (IQS Directory, n.d.).

2.2.1 PP- Polypropylene

PP is made by the polymerisation of propylene. Propylene, a class of hydrocarbons, is a gaseous compound obtained from the thermal cracking of ethane, propane, butane, and naphtha fraction of petroleum (The Editors of Encyclopaedia Britannica, 2017). Some of the properties of PP include toughness, lightweight, heat and chemical resistance, these properties can be changed which can give different types of PP that can be used in different

areas like packaging, automotive industry, consumer products like furniture, kitchenware etc (Hindle, n.d.).
Even though PP has many advantages and is used in many places it has some disadvantages that must be considered.The disadvantages can be degradation by UV radiation, negatively affected by chlorinated solvents, and the presence of some metals, which accelerate oxidative degradation (Maddah, 2016).

2.2.2 PE- Polyethylene

PE is one of the most used plastic type in the world which is used in millions of products across different areas like packaging, automotive, electrical etc. PE is a lightweight durable thermoplastic which is made from polymerisation of ethylene monomer. The different versions of PE are due to the different ways in which the polymer structure is arranged. Branched versions of PE include LDPE and linear version of PE include HDPE (Omnexus, n.d.).

- HDPE - is a cost effective thermoplastic with a linear structure manufactured at low temperatures and low pressures. Some of the advantages of HDPE include temperature resistance, excellent insulating properties, and weather resistance. The disadvantages include high stress cracking, poor UV-radiation resistance. HDPE is used in several packaging solutions for example crates, bottles, storage containers etc (Omnexus, n.d.).
- LDPE - is a semi-rigid and translucent polymer manufactured at high temperatures and pressures. Some of the advantages of LDPE are high temperature resistance, high impact strength, and chemical resistance. The disadvantages include high gas permeability particularly carbon dioxide, poor UV resistance, and highly flammable. LDPE is used in different applications like laminations, bottles, films, and closures in the packaging industry and water pipes and hoses for the pipes and fitting industry (Omnexus, n.d.).

2.2.3 PS-Polystyrene

PS is a naturally transparent and synthetic thermoplastic produced by the polymerisation of styrene (The Editors of Encyclopaedia Britannica, 2018). PS can be found in solid plastic and rigid foam types. These materials can be seen in many products in the food industry, automotive industry, electronics and packaging industries around the world (Chemical Safety Facts, n.d.). Some of the advantages of polystyrene are high tensile strength, high temperature resistance, and being naturally transparent. The disadvantages include high flammability harmful to the environment, and recycling is possible however expensive (Habib, 2021).

2.3 Circular plastic usage in the construction sector

There are many definitions for circular economy, one definition is the one made by Benton et al.(2015) “A circular economy is one where the resources coming into the economy are not allowed to become waste or lose their value. Instead, this economy would recover those resources and keep them in productive use for as long as possible.” (s.17). The core

principles of circular economy are eliminate, circulate, and regenerate which puts focus on eliminating waste and pollution, increasing resource usage efficiency and regenerating nature.
Circular strategies are essential for reducing plastic use in the construction sector. There are four main categories to reduce the environmental impacts plastic has in the construction sector.

- Alternative material manufacturing
- Material efficiency
- Reusing
- Material recycling at the End-of-Life

2.3.1 Alternative material manufacturing

Recycled plastic demand less energy and emits less carbon dioxide when it is manufactured. Compared to the virgin plastic raw material emits is 0.7 ton CO_2-eq compared to virgin plastic which emits 2.3 ton CO_2-eq . However plastic loses some properties when recycled depending on the polymer, therefore some amount of virgin material needs to be added. Recycled plastic comes from collection of plastics but mostly from production waste (Almasai et al., 2019).
There is also renewable plastic that is biobased. These materials often comes from starchy crops for example corn and sugar cane but could also be from cellulose from trees and herbal oils. (Almasai et al., 2019). Biobased materials are difficult to recycle and are often incinerated. It also needs to contain certain properties to be incinerated (Waste management company, personal communication, 4 February 2022).
Two examples for recycling opportunities are EPS insulation which is possible to reuse, it can be collected, compressed and recycled to make new EPS blocks. This method is 100 % recyclable (Almasai et al., 2019). However, at some construction sites, EPS usage is limited due to fire hazards and is only used as an insulation material.
Another example is PE packaging plastic. A study made by Mistra closing the Loop made composite plank with PE packaging plastic. Two tons of waste from NCC construction site were reused as plastic-wood plank. It showed that it had the same physical properties as one made from virgin material (Almasai et al., 2019).

2.3.2 Material efficiency

The essence of material efficiency is to reduce resources needed for a product or processes. For instance, by having less material but with the same function, less energy for a certain process or by reducing waste or making the product last longer so it doesn't need a replacement. Standards like Leadership in Energy and Environmental Design (LEED) and Environmental Product Declaration (EPD) recommend the use of materials which stable and durable thus having a longer life and produced from processes that are energy efficient (Almasai et al., 2019).

2.3.3 Reuse

As a global effort to move away from single use plastics, the concept of reusing packaging plastic is gaining attention and is considered a crucial step toward reducing plastic pollution (Ellen Macarthur Foundation, 2019). Investigation has shown the effects of re-using plastic is much better in terms of resource consumption when compared to linear models even when considering transportation thus having a less overall impact on the environment ((Ross and Evans, 2003)). Some of the benefits associated with reusing plastic packaging includes reduced labour costs, costs associated with waste disposal processes, improved product flow, and reduced cost of packaging (Gardas et al., 2019).

2.3.4 Material recycling at the End-of-Life

It is important to design plastic for the purpose of recycling so it does not contain any harmful substances etc. Biobased plastic could be a problem in Sweden depending on which plastic type it is and as of today, there are no major industrial composting sites (Waste management company, personal communication, 4 February 2022). However, there could be bio plastics that are called "drop-in" plastic where they have the same physical and chemical properties as fossil plastic and could therefore be used in existing recycled plants (Almasai et al., 2019).
Sorted plastic types are desirable at the waste management companies since it requires them to spend less time and energy from performing the additional sorting steps that are required thus making it economically viable (Waste management company, personal communication, 4 February 2022).

3
Applied methods

A brief description of the steps performed in this project are explained below.

3.1 Literature review

A literature review was conducted as the first phase in the methodology, to gather information on plastic production and packaging plastic in the construction industry and also to answer the research questions as seen in the section 1.2. Certain data repositories were used to find the relevant research articles. Google scholar, Sciencedirect, Researchgate and Scopus were used. The initial literature review gave an overall understanding the production of plastics, different types of packaging plastics and their properties, packaging plastics in the construction industry, various stakeholders involved, present challenges and possible opportunities. The second phase involved gathering data to map the system and perform life cycle assessments. The data was collected from public data repositories, involved stakeholders, and stakeholder interviews. The third phase involved formulating and assessing circular strategies.

3.2 Stakeholder interviews and Site visit

The project team has conducted a semi structured interview with a waste management company to understand the end-of-life processes that plastics undergo once they are picked up from different sites. The interview started with questions that covered general topics and scoped them down to technical and precise questions. Finally, ended with reflective/evaluative questions about challenges and possible opportunities.
A site visit was conducted at a construction site in Västra Götaland. The construction site was for a new skyscraper between 20-40 floors. It has a concrete foundation and windows surrounding the entirety of the building. There were relatively few waste containers as the construction site is under limited space. The main aim of the site visit was to get an understanding of the packaging plastic flows into the site and use the information gathered, to map the system. The team looked into various processes that required different plastic products and the type of plastic used for that product. The packaging plastic types observed at the site were PE, PP, PS, LDPE and PET. Additionally, pictures of the various collection containers were taken to act as visual guidance, to understand how sorting takes place.
The site visit was then concluded with a structured interview with the Quality and Environmental leader at the site. The team asked various questions related to challenges affecting the present system and future opportunities that can be investigated.

3.3 Plastic handling at construction sites

The construction company is a large business with over 100 projects around Sweden. The projects could be new buildings, infrastructures, renovation and demolition projects.

The packaging plastic comes from suppliers to the construction sites and is thrown into waste containers after the intended use. The containers are categorised according to the type of waste they contain, defined by the waste handling company. These containers are collected by the waste handling company at regular intervals where the contents of the containers will go through end-of-life processes. The different categories of waste containers are :

- Plastic packaging - This plastic waste comes from household packaging plastic which is often from the office spaces. The recycling company "Svensk plast återvinning" is recycling about 10-20% of the plastic that is thrown and about 80-90% is sent to incineration (Waste management company, personal communication, 4 February 2022).
- Plastic packaging, other - The plastic from industrial use, such as drums, buckets, product wrapping, and films appears in this container. The plastic types are mixed and depend on the state of construction sites, but it mainly contains PP and PE plastic. When recycled it is important to separate hard plastic from soft plastic (Waste management company, personal communication, 4 February 2022).
- Mixed plastic - Contains all kinds of plastic but mostly PE and PP plastic. According to the interview conducted with a waste management stakeholder, the mixed plastic containers go through singular or multiple sorting steps to separate hard plastic from soft plastic (Waste management company, personal communication, 4 February 2022).
- LDPE - Plastic film is used to protect the products during transportation to the sites and store the products at the sites. The film is easy to recycle and as observed during the site visit and stakeholder interviews the construction sites already have a system to recycle LDPE. However, the recycling process can be impacted negatively if coloured LDPE films are used.
- Combustible waste - The plastic in combustible waste is hard to trace, there have been studies showing the amount of plastic in these containers is approximately between 30-50%. Within the plastic, the amount of packaging plastic is considered to be 63% (Edo et al., 2019).
- Mixed waste - As observed, at the construction sites, mixed waste usually consists of plastic waste along with different wastes originating from a variety of construction activities. Studies, for instance Edo et al. (2019) has shown that 30% of total waste can be plastic and 63% of the plastic waste can be packaging plastic. Only 15% of the total mixed waste is recycled and the rest is incinerated, according to stakeholder interview (Waste management company, personal communication, 4 February 2022).

3.4 Material Flow Analysis

To get an understanding of the packaging plastic flows at construction sites it was important to map the system using Material Flow Analysis (MFA). The project team mapped the different types of plastics that were present at the construction sites. Different types of products and processes were also mapped and their final destination.
The procedure consists of four steps Goal & system definition, process chain analysis, balancing & accounting and evaluation (Bringezu and Moriguchi, 2018).

3.4.1 Goal & system definition

The goal of the MFA study was to map the flow of different quantities of plastic polymers from the arrival of plastic to waste management and to identify the type and the purpose of the products they are used for. The scope of the study was packaging plastic present at new construction sites across Sweden. The system boundary for MFA included the production, use, and waste management processes.
The following questions were used as guidance for the MFA.

1. What are the quantities of plastic polymers present?
2. What are the plastic products present at the sites and what are their purpose?

3.4.2 Process chain Analysis

In this stage the processes for which inputs and outputs should be quantified was identified. The flow of materials started with packaging plastic production which was transported to the construction sites across the geographical boundary as defined in the section 1.3. At the site, the polymers were used in different products, for instance, rigid packaging, buckets, bottles, jerry cans etc serving different purposes.
After the use phase, the products enter the disposal stage where they were sorted and put into their respective containers. The destination of the flow includes the waste management process which includes material and energy recycling as seen in Figure 3.1 on next page.

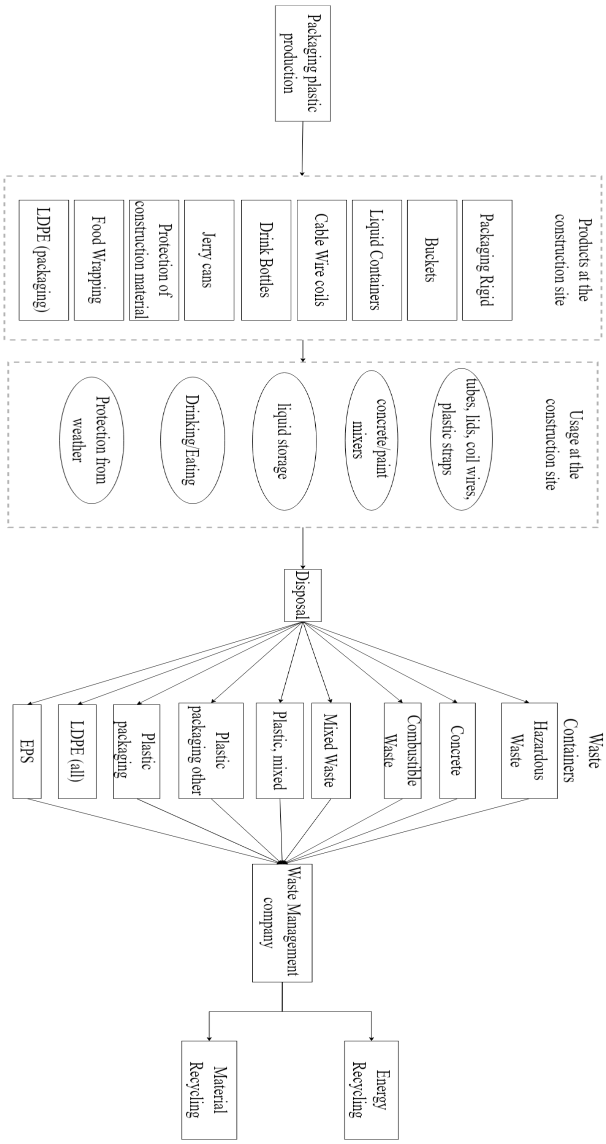


Figure 3.1: Flowchart of MFA for packaging plastic at the construction site

3.4.3 Balancing & Accounting

As mentioned in section 3.3 different containers were used to collect plastic waste. Research articles were used to estimate the different polymer quantities as it was very difficult to keep track of them in real world scenarios.

The quantity of packaging plastics present in combustible and mixed waste containers were estimated by Edo et al. (2019) and the plastic polymer percentages was estimated from Plastic Europe (2022). The polymer percentages for Plastic packaging, others are estimated from the data gathered from the site visit and stakeholder observations. For the percentage in Packaging plastic container (Stenmarck et al., 2018) was used. Due to the difficulties of sourcing data for estimating the polymer percentages in plastic mixed waste container an assumption of equal polymer quantities were assumed. A summary of these findings is presented in Table 3.1 below.

Table 3.1: Percentages of plastic polymers in different waste containers

Waste Container	Quantity of Plastics	Quantity of Packaging Plastics	PE	PP	PS	LDPE
Combustible Waste	30% (1)	63% (1)	51.3% (2)	25.6% (2)	6.3% (2)	16.8% (2)
Mixed Waste	30% (1)	63% (1)	51.3% (2)	25.6% (2)	6.3% (2)	16.8% (2)
Plastic packaging, others	NA	NA	50% (3)	50% (3)	NA	NA
Plastic packaging	NA	NA	16% (4)	22% (4)	3% (4)	36% (4)
Plastic mixed	NA	NA	25% (3)	25% (3)	25% (3)	25% (3)
LDPE	NA	NA	NA	NA	NA	10.6% (5)

1. Edo et al., 2019
2. Plastics Europe, 2022
3. Own assumption
4. Stenmarck et al., 2018
5. Waste management company

3.4.4 Evaluation

The insights gained from the assessment were used to understand the flow of different quantities of polymers from the arrival to their final destination of either material or energy recycling. The data gathered from the study was used in the LCA study to assess the impacts caused by different polymer types and to formulate circular strategies.

3.5 LCA

After the quantities and flows of the packaging plastics were mapped with MFA, an LCA was conducted. The importance of the LCA was to calculate the environmental impacts associated with each packaging plastic type was responsible for, thus acting as a base scenario which can be further compared upon.

3.5.1 Goal and Scope definition

The goal of the LCA study was to evaluate the emissions from the packaging plastics and use the data to formulate circular strategies which help improve the circularity of

packaging plastic in the construction industry.
The intended audience for this LCA study was the stakeholders involved with decision making at in the construction sector.

1. **Functional Unit** - The functional unit was considered to be 1 kilogram of plastic granulate production. The decision to select the functional unit was related to the subjects that are studied and to the goal of this project, as it makes it easier to compare the emissions for different plastic types across different processes in their life cycle.
2. **Flow Chart** - The Figure 3.2 shows the flow of packaging plastic at the construction sites. It starts with raw material extraction followed by granulate production. The polymer granulates of different types are sent to various plastic packaging producers where different packaging products were made. The products are then transported to the various construction sites, some of them include buckets, liquid containers, jerry cans, packaging film, and rigid packaging which are used for storage and protection. After the intended use the packaging plastic is placed in containers classified for different types of wastes like Combustible, Mixed waste, Plastic packaging, Packaging plastic, others, Mixed plastic and LDPE. These containers will be collected by the waste management company where the materials will undergo material recycling processes and energy recycling where the heat produced would be used in district heating.

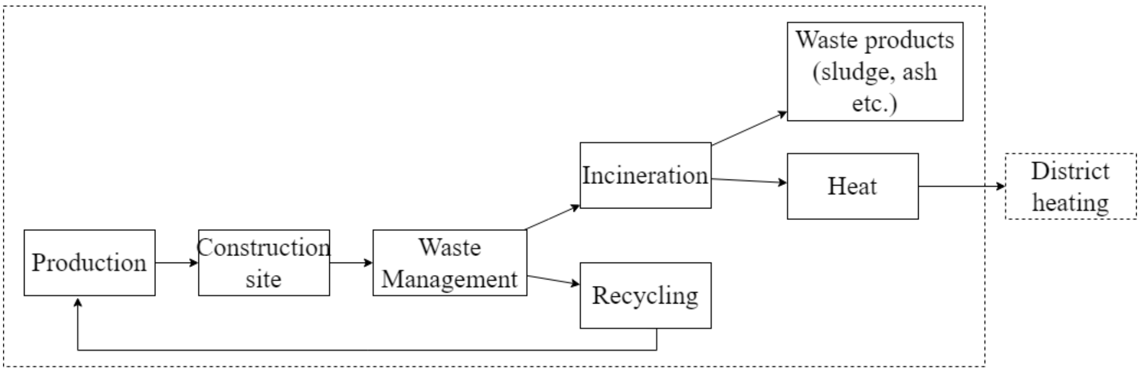


Figure 3.2: Packaging plastic flow for construction sites, including production and end-of-life

3. **Modelling of the system** - The modelling of the system and the categorising of the different life cycle stages within the system were done according to the European standard EN 15978 "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method" (SIS - Bygg och anläggning, 2011) as seen in Figure 3.3.

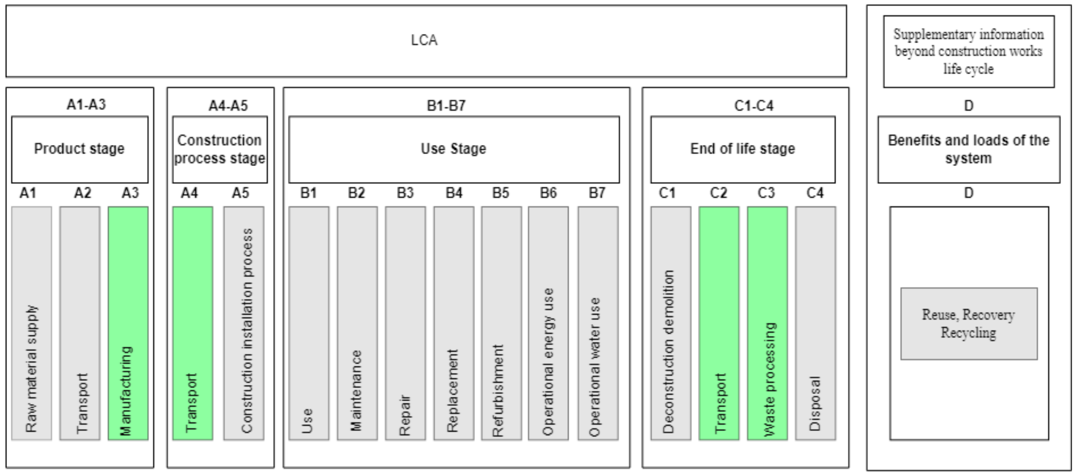


Figure 3.3: System modelling according to EN 15978 "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method"

Product stage (A1-A3) - The first step of the system was the product stage, where the cradle-to-gate processes were considered. A1, the raw material supply, which is excluded from the system due to a variety of suppliers providing packaging plastic. Since different types of plastic and the location of suppliers were unknown, gathering data would be difficult. A2, the transportation of raw material to the production plant, was also excluded with the same reasoning as above. A3, the manufacturing process, was included in the system. The manufacturing process for the plastic was considered generic for each plastic type and would have the same emissions irrespective of the suppliers.

Construction stage (A4-A5) - A4, the transportation distances, from plastic packaging manufacturers to the construction sites were included in the system, even though suppliers were unknown. A5, the installation, dismantling and storing of packaging material was excluded from the system as they negligible environmental impacts.

Use stage (B1-B7) - The use stage was excluded from the system. Most of the packaging plastic that arrives at the construction sites was dismantled directly and sent to waste containers. The use,maintenance, and repair and operational usage process were assumed to have no environmental impact.

End-of-life stage (C1-C4) - In the end-of-life stage packaging plastic was sent to waste management companies. C1, the deconstruction demolition stage where the packaging plastic was sorted into different containers at the site and it was assumed to have zero environmental impacts. C2, the transportation of the waste containers to either incineration or recycling sites. C3, waste processing where the plastic waste was either incinerated for district heating or sent to recycling plants where the recovered plastic was used to create new plastic packaging. System expansion was used for district heating by incineration.

Benefits and loads of the system (D) - The benefits of certain processes were not taken into consideration. The material recovery, in form of plastic packaging from the recycling, was sent back into the manufacturing process as a substitute for virgin raw material.

4. **Type of LCA** - Attributional LCA was used as it provides environmental impacts that can be linked to the product in the study (Ekvall, 2020). The decision to choose attributional LCA was influenced by its many positive aspects a) feasibility, because of the abundance of the availability of average data compared to the marginal data. b) accuracy, as the need for accurate data for consequential LCA's might make them less feasible and might not guide the decision makers to make improvements unlike attributional LCA's. c) comprehensibility, as attributional LCA's follows the concepts of "life cycle" and "value chains" making it transparent and easy to communicate to the stakeholders and decision makers. (Ekvall, 2020).
5. **System Boundaries** - The LCA study included production of the granulates, transportation of the products to the sites and End-of-Life processes. The geographical boundary for the LCA was packaging plastics at new construction sites irrespective of their stage of construction and type of construction across Sweden.

3.5.2 Inventory Analysis

1. **Data collection** - The data for the LCA study was gathered from stakeholders, MFA, the database repository Ecoinvent, stakeholder interviews, and research articles. In the case where data was missing, assumptions were made with stakeholders involved and relevant research articles.
   - **Product Stage (A1-A3)** - The LCI data for A3 was taken from Ecoinvent 3.8 with data representing Europe (RER).
   - **Construction process stage (A4-A5)** - The accurate data for the transport distances (A4) were not available due to confidentiality reasons hence an assumption of 500 kilometres was made and the transport vehicle was assumed to be a freight lorry 16-32 metric tons, Euro 6 taken from Ecoinvent 3.8 dataset representing Europe (RER). The LCI data for installation and dismantling (A5) processes were not collected since the environmental impacts from storing and dismantling packaging plastic are considered to be zero.
   - **Use stage (B1-B7)** - The processes under this stage were related to use and not considered in the system. Maintenance (B2), repair (B3), and replacement (B4) of packaging plastic after the construction was finished is not considered, as it has negligible environmental impacts.
   - **End of life stage (C1-C4)** - The processes under this stage include deconstruction demolition (C1), transport (C2), waste processing (C3), and Disposal (C4). The LCI data for the transportation of products (C2) to the waste management facilities was assumed to be 50 km and the transport vehicle was assumed to be freight lorry 16-32 metric tons, Euro 6 taken from Ecoinvent 3.8 representing Europe (RER). The waste processing included incineration and recycling for which the LCI data was gathered from Ecoinvent 3.8 with datasets representing Sweden (SE) and Europe without Switzerland respectively.
2. **Allocation** - In compliance with the ISO allocation procedure ISO 14041 (Baumann and Tillman, 2004) allocation was avoided by expanding the system. In the end-

of-life, incineration, the heat from the process was used as an input to the district heating process. The heat credits the system with an environmental load that would have occurred if the same amount of heat had been produced from an alternative fuel (Baumann and Tillman, 2004).

3.5.3 Impact Assessment

This stage involved translating the environmental loads from the inventory results into environmental impacts. The general category of environmental impacts included resource use, human health and ecological consequences. CML impact assessment method created by the University of Leiden in the Netherlands in 2001 was used and the impact categories of global warming potential, human toxicity, abiotic resource depletion (fossil fuels), eutrophication and acidification were selected (Baumann and Tillman, 2004).

3.5.4 Interpretation

As defined in ISO 14040 standards this stage of the study involved assessing the impacts from different stages in the life cycle study and combining them with goal and scope of the study to reach conclusions or recommendations (Baumann and Tillman, 2004). Since there were some unreliable data in the LCA, a worst case scenario and a best case scenario have been formulated to act as a reference to other strategies. In the worst case scenario, only 15% of mixed waste was recycled, and the rest of the waste from all containers was incinerated. In the best case scenario, 85% of mixed waste and the entirety of combustible waste were incinerated while the rest of the waste was recycled.

3.6 Circular strategies ideas

Circular strategy development was needed to achieve efficient plastic usage. It started with an idea generation exercise with the purpose to generate possible strategies that could be applied, irrespective of their implementation capability. To cover a broad range of resource efficient concepts, 7 design principles with adaptation for circular economy were used, as Lars Almefelt explained in the lecture "Product Design and Development, from Principles to Synthesis of Resource-efficient solution" (personal communication, 15 September, 2021).

- Modularisation - Circular strategies that promote the opportunities for better material usage.
- Lightweight design - Material and energy efficient strategies to improve resource consumption.
- Material Selection - Select better materials that have lesser environmental impacts.
- Function Sharing - Utilising a single module/component to achieve various functions, thus reducing the number of components, total mass, and space.
- Servitization - Improving the material usage rate by enabling co-consumption.
- System Consideration - Enabling flexibility for the products or services to evolve into more efficient versions in the future.
- Longevity - Designing products for maintenance, upgrading, reuse and re-manufacturing increasing its lifetime.

3.6.1 Assessing circular strategies

After the ideation exercise a total of 25 possible circular strategies as seen in Appendix A.1 were created. The selection of the strategies with the least amount of environmental impact will be done in two step screening process.

The first step of the screening test used the strategic design framework formulated by (Baldassarre et al., 2020) to assess the strategies with respect to:

- Desirability - Does the circular strategy align with the stakeholder's goal and values?
- Viability - Is it financially viable to implement the circular strategies?
- Feasibility - Is it technically possible to implement the circular strategy?

The selected strategies will be used in the second part of the screening test where they will be assessed for an additional dimension.

- Sustainability - Does the circular strategy promote positive changes across social, economical and environmental dimensions?

The purpose of this two step selection process was to find strategies that fulfil the organisational goals while integrating environmental and societal concerns. A series of questions were formulated under each assessment category to direct the project group to assess and select the best strategy possible (Baldassarre et al., 2020).

3.7 Strategy selection

The guiding questions for the first and the second screening tests along with the table containing the selected strategies are shown below.

3.7.1 First Screening test

The questions formulated for different assessment categories for this screening test are presented below. The strategy was considered to be passed when it satisfied all the required criteria.

- Desirability:
  - Does the strategy support the construction company to reach its goals?
  - Will the strategy be compatible with the waste management companies?
- Viability:
  - Is it future proof?
- Feasibility:
  - Is it possible to implement?
  - Can suppliers supply the desired products?
  - Will the workflow be the same?
  - Is the strategy quantitative? *

*Qualitative strategies will be assessed after LCA calculations.

3.7.2 Second Screening test

The strategies that passed the first test will be assessed with respect to sustainability dimension. To measure the environmental impacts from the strategies openLCA software tool was used. The questions formulated for this dimension are presented below.

- Sustainability:
  - What are the environmental impacts generated by the strategy?

4

Results

This section provides the details of the calculations that has been performed.

4.1 Results of Material Flow Analysis

The percentages of plastic types with respect to total packaging plastic is shown in Table 4.1 and different plastic types present in the waste containers is shown in the Table 4.2.

Table 4.1: Percentage of plastic types in total packaging plastic

Plastic Type	Percentage present
PE	41,43%
PP	25,12%
PS	11,50%
LDPE	21,95%

From Table 4.1 it can be seen that the highest percentage of plastic type is PE with 41,43% among the total packaging plastic and the lowest is PS with 11,50%.

Table 4.2: Percentages of plastic types present in the waste containers

Plastic Types	PE	PP	PS	LDPE
Combustible	51,50%	42,70%	22,70%	32,10%
Mixed waste	28,50%	23,40%	12,50%	17,00%
Plastic Mixed	17,70%	29,00%	63,70%	33,40%
Plastic packaging, other	0,70%	1,20%	0,00%	0,00%
Plastic packaging	1,60%	3,70%	1,10%	6,90%
LDPE packaging	0,00%	0,00%	0,00%	10,60%

From the total amount of packaging plastic the individual amounts of plastic types, present in different waste containers are shown in the Table 4.2. PE has its highest share in Combustible waste 51,50% and its smallest in Plastic packaging, others 0,70%. PP have its highest in Combustible waste container at 42,70% and lowest in Plastic packaging other at 1,20%. PS has its highest amount in Plastic mixed and lowest in Plastic packaging at 63,70% and 1,10% respectively. LDPE however has its highest share in Plastic mixed and lowest in Plastic packaging at 33,40% and 6,90% respectively, however its the only plastic type present in LDPE packaging.

4.2 Selected Scenarios

The strategies that passed the screening tests are highlighted in green colour and the strategies that might meet the criteria and have a meaningful potential are highlighted in orange colour. The strategies that are qualitative will be assessed in the discussion, as seen in table 4.3 below.

Table 4.3: Circular Strategies selection

Circular Strategy ID	Design Principle	Desirability	Viability	Feasibility
1: More LDPE Plastic	Modularisation	Yes	Yes	No
2: Buckets reusing	Modularisation	Yes	Yes	No
3: Package repurposing	Modularisation	Yes	Yes	Qualitative
4: Reuse PP bands	Modularisation	Yes	No	No
5: Take back system	Modularisation	Yes	Yes	Maybe
6: Reuse Jerry cans	Modularisation	Yes	Yes	No
7: Lightweight packaging	Lightweight design	Yes	Yes	Maybe
8: Reduce plastic	Lightweight design	Yes	Yes	Maybe
9: Less plastic types	Material Selection	Yes	Yes	Yes
10: PLA (Bio Plastic)	Material Selection	Yes	Yes	Yes
11: Cardboard Packaging	Material Selection	Yes	Yes	Yes
12: LDPE (transparent)	Material Selection	Yes	Yes	Qualitative
13: Transparent plastic	Material Selection	Yes	Yes	Qualitative
14: No double packaging	Function Sharing	Yes	Yes	Qualitative
15: Container (every floor)	Function Sharing	Yes	Yes	No
16: One big container	Function Sharing	No	No	No
17: Same plastic same time	Servitisation	Yes	Yes	Maybe
18: Standardizing	Servitisation	Yes	Yes	Yes
19: Awareness Programs	Servitisation	Yes	Yes	Qualitative
20: NCC sites reuse	Servitisation	Yes	Yes	Qualitative
21: Electric trucks	System consideration	Yes	Yes	Yes
22: Less transport	System consideration	Yes	Yes	Maybe
23: Multiple containers	System consideration	Yes	Yes	Maybe
24: Reusing plastic	Longevity	Yes	Yes	No
25: Design for repurposing	Longevity	Yes	Yes	No

4.2.1 9. Less plastic types

Four main plastic types PE, PP, PS and LDPE are studied in this report. This circular strategy aims to improve the time and effort to sort, which in turn increases the recycling potential and also provides an opportunity to eliminate plastic types that cause high environmental impacts.
Commonly used chemical materials in construction sites are concrete curing compounds, release agents, bonding agents and different types of protective and decorative coatings (Ravi Nissanka, 2011). These construction materials contain chemical substances like

acrylic, epoxy resin, amine based chemicals and polyvinyl acetate (Structural Guide, n.d.; Commercial Construction Renovation, 2021; Evonik, n.d.).
The above mentioned chemical substances can be hazardous and volatile hence care should be taken while storing them (Health and Safety Authority, n.d.). The plastic types used in products that contain these chemical substances should be resistant to the chemicals. Polyethylene (PE) is resistant to aqueous solutions of salts, acids and alkalis due to its non-polar nature. PE is chemical resistant to the correlated chemicals found in construction materials (Braskem, 2005a). Polypropylene (PP) also has similar resistance to chemical substances present in construction materials (Braskem, 2005b).

4.2.2 10. PLA (Bioplastic)

PolyLactic Acid (PLA) is a biobased polymer made from corn starch with physical and chemical properties similar to PET and PS (Madival et al., 2009). With recent trends directed towards phasing out fossil fuels, a biobased polymer stands as an interesting option to look into. The strategy is to replace the hard plastic types with PLA. The quantity of PLA was assumed to be the sum of PE, PP and PS present at the sites.

4.2.3 11. Cardboard packaging

LDPE is replaced with Cardboard. In the openLCA software the total amount of cardboard is assumed to be equal to the total amount of LDPE present at the construction sites.

4.2.4 18. Standardising

The strategy benefits the sorting of different plastic types. If the same type of product always has the same plastic type, which will require less effort to sort. An example can be buckets made from the same plastic type are thrown into a container which only consists of the same plastic type. This is applied to all the plastic products at the construction site. In openLCA 50% recycling level will be modelled with the plastic types having the same share as BAU.

4.2.5 21. Electric trucks

Since electric trucks have lesser environmental impacts when compared to a diesel truck and given the fact that the waste management companies stay within the city borders, this strategy promotes the use of electric trucks when transporting the waste containers from the sites to the waste management facilities.

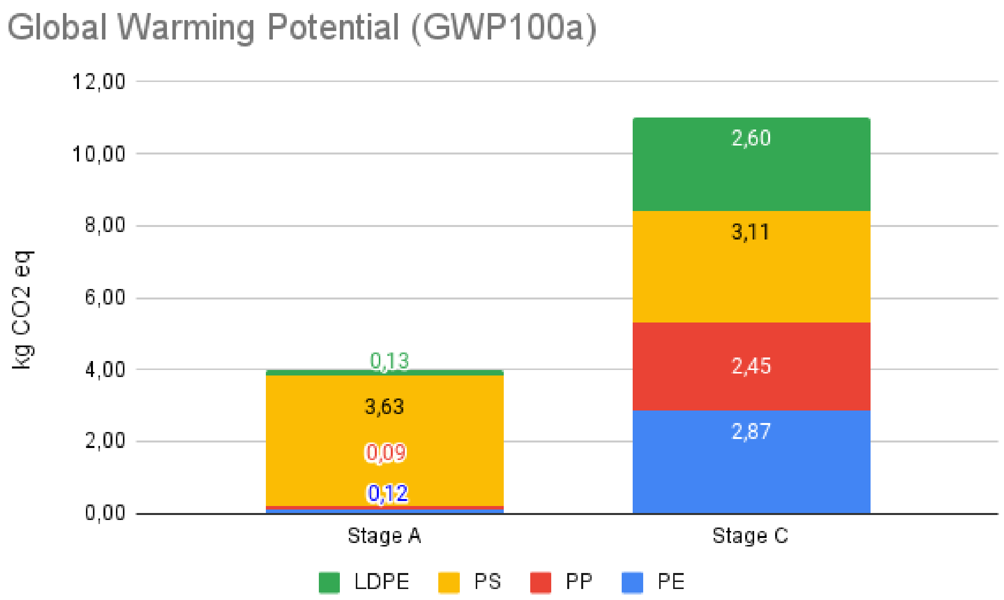
4.2.6 22. Less transportation

This circular strategy promotes the overall reduction of transportation by assuming all the suppliers of raw materials, packaging plastic production, and the construction sites are closer to each other. In order to model the changes in openLCA the average transportation distance was changed from 500km to 250km.

4.3 LCA

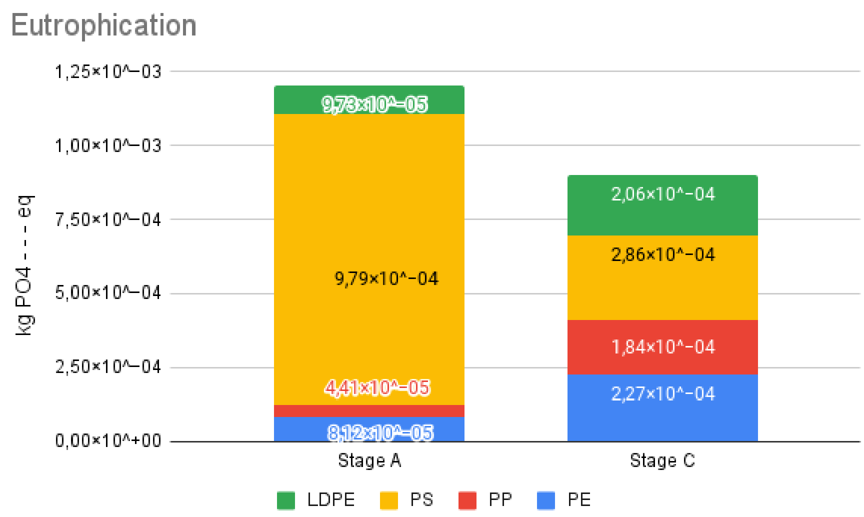
The results are divided into stage A, which includes product stage (A1-A3) and construction stage (A4-A5) and stage C, which includes end-of-life stages (C1-C4). The environmental impacts from the use stage (B1-B7) is assumed to be zero and not included, as stated in section 3.5. The results are also divided into each plastic type for a better understanding of how each plastic type is affecting the system.
The results for the chosen impact assessments as stated in the section 3.5 are shown below. The different plastic types are colour coded: Green-LDPE, Yellow-PS, Red-PP, Blue-PE.

Figure 4.1: BAU case with the different plastic types (GWP 100a)



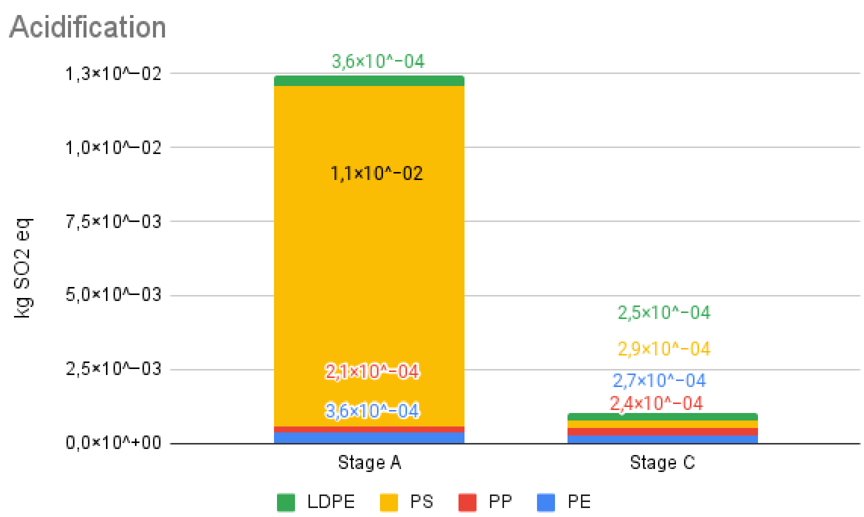
As seen in Figure 4.1, in stage A, PS contribute to the highest GWP at 3,63 kg CO_2 eq per kg plastic and GWP of PP is lowest at 0,09 kg CO_2 eq. In stage C the plastic types producing the highest and lowest GWP are PS at 3,11 kg CO_2 eq and PP at 2,45 kg CO_2 eq respectively.

Figure 4.2: BAU case with the different plastic types Eutrophication



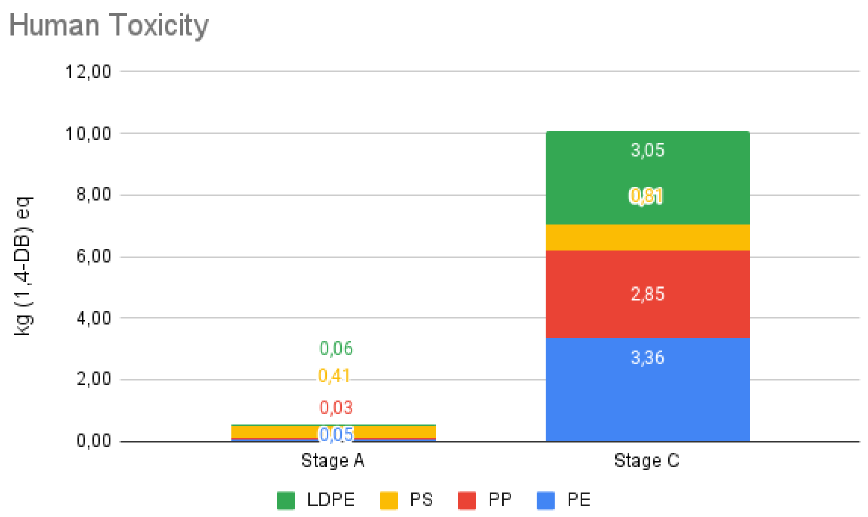
As seen in Figure 4.2. the highest eutrophication impacts in stage A is PS at $9,79 * 10^{-4}$ kg PO_4^{-3} eq and the lowest is from the plastic type PP at $4,41 * 10^{-5}$ kg PO_4^{-3} eq. In stage C, the highest eutrophication impact is caused by PS at $2,86 * 10^{-4}$kg PO_4^{-3} eq and the lowest eutrophication impact is caused by PP at $1,84 * 10^{-5}$ kg PO_4^{-3} eq.

Figure 4.3: BAU case with the different plastic types acidification



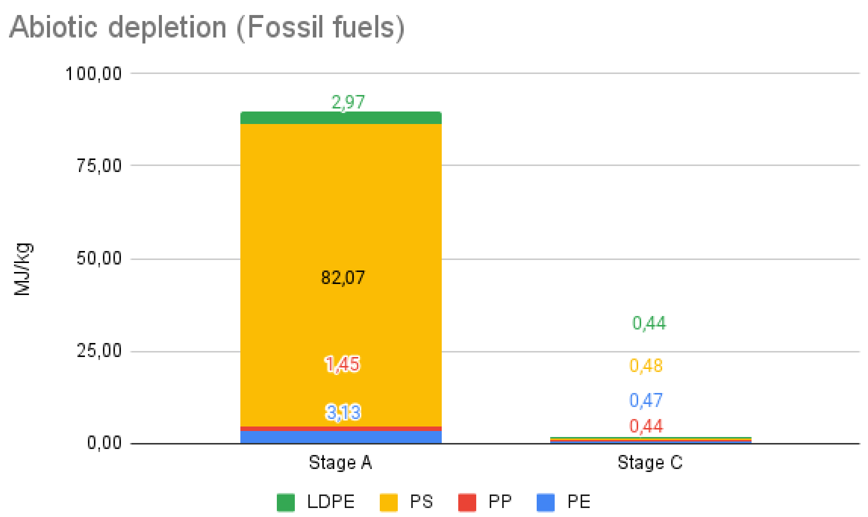
As seen in Figure 4.3, the highest acidification impact in stage A is from PS at $1,1 * 10^{-2}$ kg SO_2 eq and the lowest impact is from PP at $2,1 * 10^{-4}$ kg SO_2 eq. In stage C, the highest acidification impact is caused by PS at $2,9 * 10^{-4}$ kg SO_2 eq and the lowest impact is caused by PP at $2,4 * 10^{-4}$ kg SO_2 eq.

Figure 4.4: BAU case with the different plastic types Human toxicity



From Figure 4.4 it can be observed that the highest human toxicity is caused by PS at 0,41 kg (1,4-DB) eq and the lowest impact is caused by PP at 0,03 kg (1,4-DB) eq. The highest impact in stage C is from PE at 3,36 kg (1,4-DB) eq and the lowest is from PS at 0,81 kg (1,4-DB) eq.

Figure 4.5: BAU case with the different plastic types Abiotic depletion (Fossil fuels)

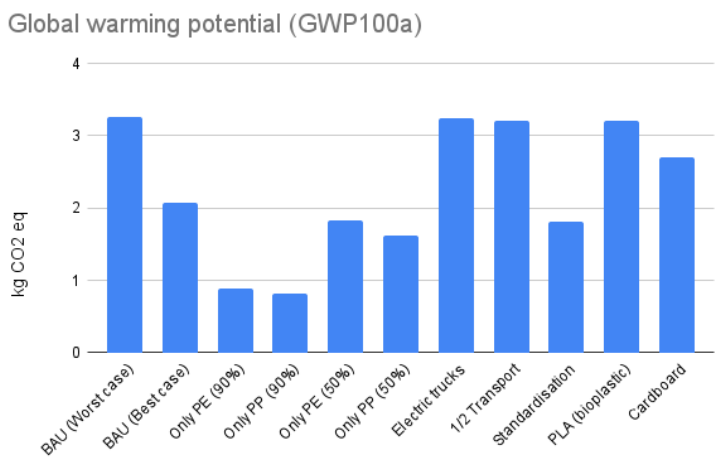


From Figure 4.5 it can be seen that the highest abiotic fossil fuel depletion in stage A is caused by PS at 82,07 MJ/kg and the lowest impact is from PP at 1,45 MJ/kg. In stage C the highest impact is caused by PS at 0,48 MJ/kg and the lowest impact is caused by both PP & LDPE at 0,44 MJ/kg.

4.3.1 Comparison between Circular strategies

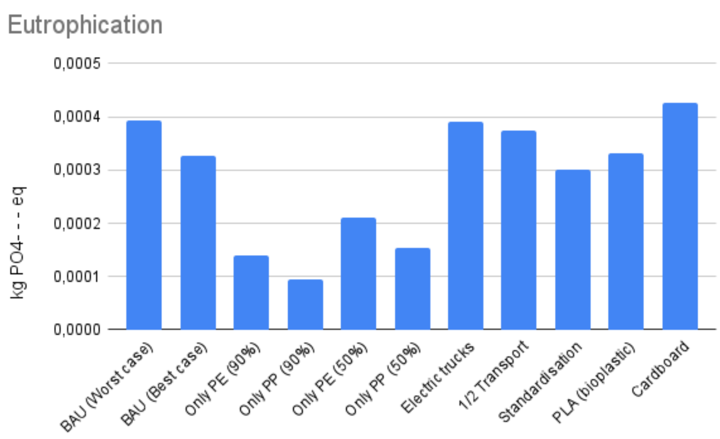
Circular strategies as mentioned in the section 3.6.1 are modelled in the openLCA software. The results for the different impact categories for each strategy are shown below.

Figure 4.6: Circular strategies comparison, (GWP 100a)



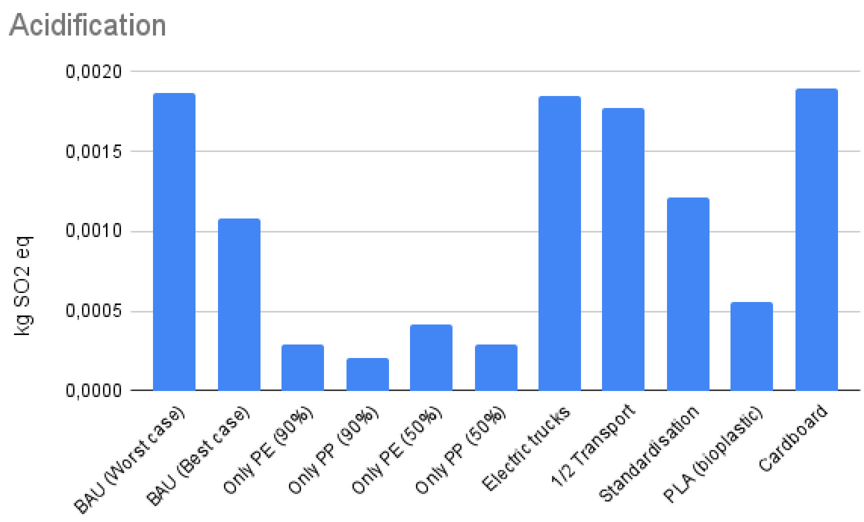
As seen in Figure 4.6 Only PE (90%) and Only PP (90%) recycling scenarios have the lowest GWP. While the scenarios with Electric trucks, Half transportation, PLA (bioplastic) and Cardboard show a marginal change. There is a large difference from BAU (worst case) to BAU (best case), Standardisation, Only PE (50%), and Only PP (50%) scenarios.

Figure 4.7: Circular strategies comparison, Eutrophication



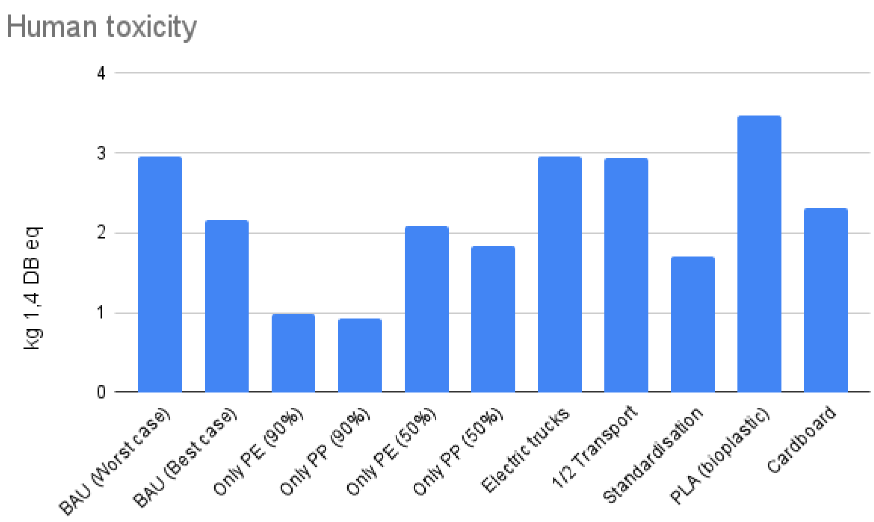
As seen in Figure 4.7 Only PE and Only PP (90%) recycling scenarios have the lowest eutrophication impacts, whereas BAU (best case), Standardisation and PLA (bioplastic) scenarios shows a large change in comparison to BAU(worst case scenario). Circular strategy with Cardboard has highest eutrophication impacts while the strategies related to Electric trucks and Half transportation shows a marginal change.

Figure 4.8: Circular strategies comparison, Acidification



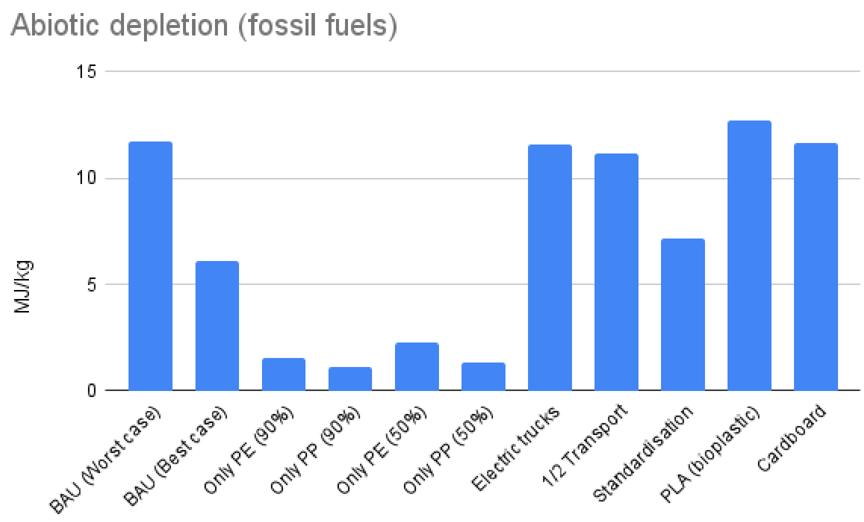
From the Figure 4.8, Only PE, Only PP recycling scenarios, and PLA (bioplastic) have the lowest acidification impacts. Whereas BAU (best case) and Standardisation scenarios has the largest positive change compared to BAU (worst case). Scenarios with Electric trucks and Half transportation have marginal changes while Cardboard has the highest acidification impacts.

Figure 4.9: Circular strategies comparison, Human toxicity



From the Figure 4.9, only PE (90%) and only PP (90%) recycling scenarios have the lowest human toxicity impacts while PLA (bioplastic) has the highest. Electric trucks and Half transportation scenarios have marginal changes to impacts from BAU (worst case) whereas BAU (best case), Only PE (50%), Only PP(50%) recycling, Standardisation scenarios show a large change when compared to BAU (worst case).

Figure 4.10: Circular strategies comparison, Abiotic depletion (Fossil fuels)

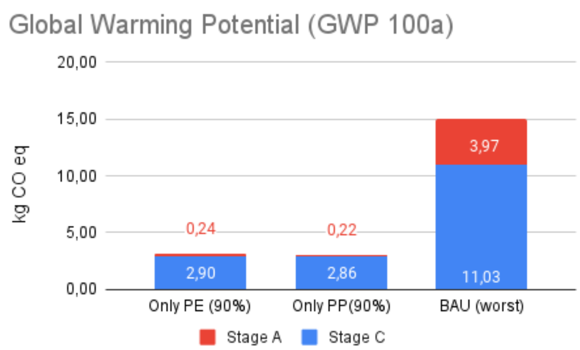


From the Figure 4.10, Only PE and Only PP recycling scenarios have the lowest impacts on abiotic fossil fuel depletion. While PLA (bioplastic) and Cardboard scenarios have the highest. The largest change can be seen in BAU (best case) and Standardisation scenarios while the Electric trucks and Half transportation scenarios have marginal improvements.

4.3.2 Only PE & Only PP

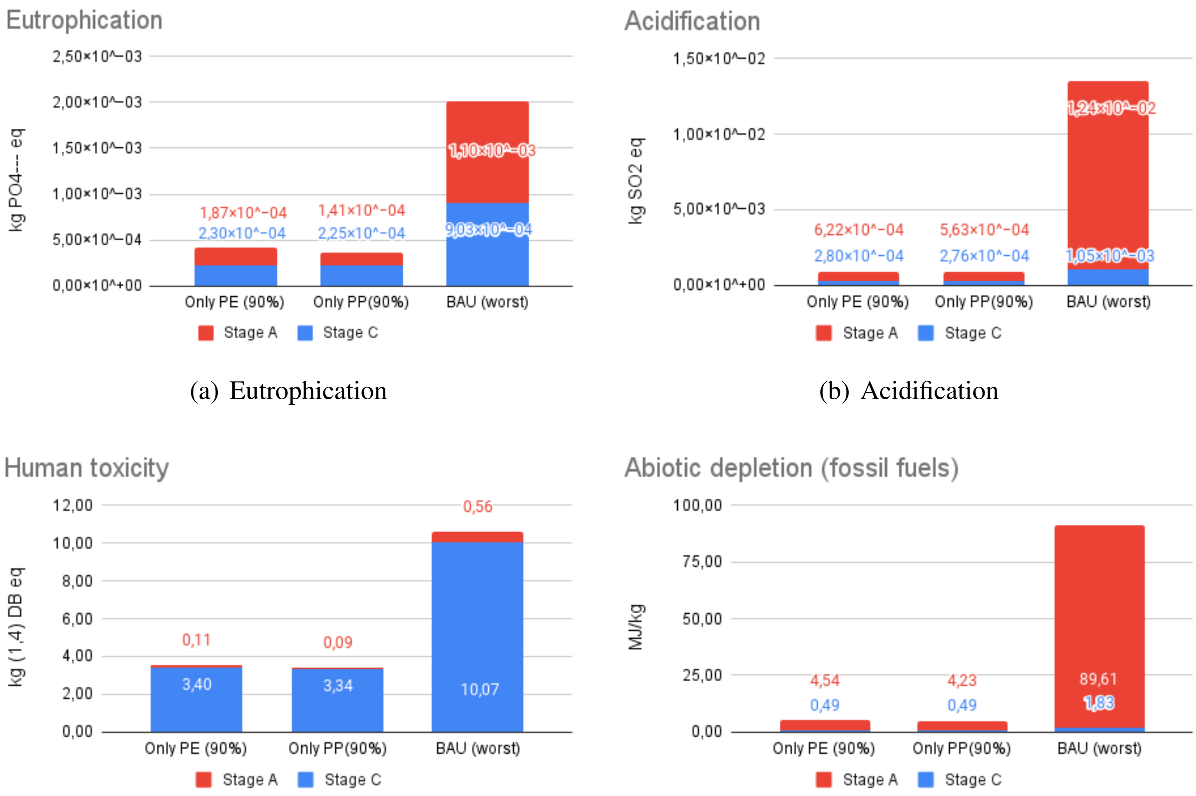
Environmental impacts across stage A and stage C for Only PE 90% and Only PP 90% recycling scenarios compared to BAU (worst case) are shown below.

Figure 4.11: Only PP 90% recycled strategy compared with only PE 90% recycled (GWP100a)



From Figure 4.11 it can be seen that GWP impacts for both the scenarios are significantly lower than BAU (worst case).

Figure 4.12: Only PP (90% recycled) compared to only PE(90% recycled) and BAU (worst case)



(a) Eutrophication

(b) Acidification

(c) Human toxicity

(d) Abiotic depletion (fossil fuels)

A similar pattern as seen in figure 4.11 for GWP can be observed in all the other impact categories, as seen in Figure 4.12. The acidification and abiotic depletion (fossil fuels) impacts having the largest difference from the BAU(worst case) scenario.

5
Discussion

In this chapter, the results and observations will be discussed below.

5.1 Present scenario

The contribution of impact categories in the present scenario differs depending on the stage and the impact categories that are being observed. In Figure 4.2, 4.3, and 4.5 it can be seen that the contribution of stage A is highest for eutrophication, acidification and abiotic depletion (fossil fuels) with PS being the major contributor. PS has 2120% more kg PO_4^{-3} eq emissions than the lowest eutrophication emitter, PP in stage A. PS also has 5138% kg SO_2 eq more emissions than the lowest acidification emitter PP and 5660% MJ/kg more emissions than the lowest adiabatic depletion which also is PP, both of them in stage A.
In comparison with the production of PP, PS has more substances that increase eutrophication, they are ammonia, chemical oxygen demand (COD) and nitrogen. Furthermore, the presence of nitrogen oxides is 1 565 600% more in PS production than in PP. The same thing follows for acidification with higher numbers for sulphur dioxide and nitrogen oxide compared to PP production. In abiotic depletion(fossil fuels) PP production uses 0.00324 kg crude oil per kg PP, while PS uses 1.004 kg crude oil kg in its production. This explains why PS has the highest emission numbers in stage A. For human toxicity, all emissions from stage A are low compared to stage C, and the plastic types have similar emissions, with PS having slightly higher emissions than the rest of the plastic types.
For GWP in stage A, as seen in Figure 4.1, PS is the single highest GWP emitter. This is because PS production has high CO_2 and methane emissions from crude oil. Stage C has higher emissions than stage A and all the plastic have similar GWP, it differs by 27% for the highest and lowest emitter. Stage C has higher emissions because in its end-of-life process most of the plastic is incinerated and therefore has high CO_2 emissions.
The emissions from stage C, eutrophication, acidification, and abiotic depletion are lower than in stage A and the plastic types have similar emissions to each other. Except for human toxicity where stage C is the highest stage and PS is the lowest emitter and PE is the highest emitter, see figure 4.4. That is because vanadium is the biggest health risk in the waste incineration process.

5.2 Improving the system

The selected circular strategies outlined in section 4.2 were assessed for the selected impact categories. From a quick glance, it can be seen that the strategies with an emphasis on recycling have a larger change compared to the present scenario indicating that the higher the recycling percentage, the lesser the impacts.

5.2.1 Business as usual

Comparing the present scenario and BAU (best case) scenario it can be seen that the best case scenario has lesser impacts across all the impact categories as seen in Figures 4.6, 4.7, 4.8, 4.9, and 4.10. In the present scenario, only 5.8% of total packaging plastic is recycled while in the best case scenario 40% of packaging plastic is recycled. The packaging plastic present in the Plastic mixed container and Plastic packaging, others container which is 30% of the total plastic used, is assumed to be recycled because of the lack of information on the exact quantities. Hence the variation of impacts between the two scenarios shows that recycling has a bigger impact but also indicates the importance of the availability of data and how it can influence the results.

5.2.2 Less Plastic types

This circular strategy focused on eliminating the different plastic types thus increasing the recycling potential and has the least amount of impact among all the other strategies. Two recycling scenarios 90% and 50% were assumed by changing all the hard plastic present at the construction sites to PE or PP, the chemical properties have been considered to make sure the changes are possible. Additionally, scenario of 50% recycling is considered because achieving 90% recycling target might be difficult in the real world given different working conditions at the construction sites. But as seen in the Figures 4.6, 4.7, 4.8, 4.9, and 4.10 even reaching a 50% recycling target has a significant change compared to the present scenario.
Observing the stage contributions of Only PE (90%) and Only PP (90%) recycling scenarios across the impact categories as seen in Figure 4.11 and Figure 4.12, on average the present scenario has 974% more emissions for all impact categories when compared to Only PP (90%). The lower impacts from Only PE and Only PP are due to the fact that changing the hard plastic to either PE or PP reduces the effort to sort plastics at the construction sites increasing the recycling potential. This strategy also provides the opportunity to replace PS which has more environmental impacts per kg compared to other plastic types. Even though there are many positive aspects attached to this strategy a hindering factor can be the capability of the suppliers to supply the products with the chosen plastic type. Therefore, it might be more viable to use PE instead of PP, since the majority of the packaging products observed at the construction sites were made from PE.

5.2.3 Transportation

The transportation alternatives, Electric trucks for small distances and 1/2 Transportation, have a small impact on the system. For GWP, as seen in Figure 4.6 there is a small difference, the present scenario has 3,256 kg CO_2 eq while Electric trucks scenario has 3,248 kg CO_2 eq and 1/2 Transportation has 3,215 kg CO_2 eq. This shows that transportation does not have a major impact on the system. It is therefore more important to focus on other circular strategies and lower the emissions from plastics. However, it is a strategy that still lowers the emission and it is possible to combine transportation strategies with other circular strategies.

5.2.4 Standardisation

Standardisation is based on making it effortless for the construction workers to throw plastic packaging in the right container. The different plastic products should have the same type of plastic depending on the purpose. Construction workers should therefore know where to throw the waste as it is the same type of plastic for the same product. This will lead to more sorting at the site and increase the recycling, which will lead to lower emissions, which can be seen in Figure 4.6 for GWP. The present scenario has 73,46% more GWP than Standardisation scenario, that is because it has a recycle rate of 50%. This number is difficult to predict but gives an understanding of what is happening when recycling is increasing. With this method, there is a slight increase in work for the construction workers and also for the suppliers as they might have to change plastic type if they use an uncommon plastic type for the specific product. There is however more work for the purchaser at the construction site as they need to discuss which plastic to use on every product and make sure suppliers follow the agreed plastic type.

5.2.5 PLA

This circular strategy has been formulated to eliminate the use of fossil fuels in plastic production. Even though the use of bioplastics has its advantages, the production and end-of-life processes are not yet fully developed in Sweden and might need significant changes to existing systems. This will affect all the involved stakeholders. The data gathered through stakeholder interviews are reluctant to change the existing systems and instead show interest to make the existing processes more efficient.

5.2.6 Cardboard

Cardboard has been replaced instead of LDPE in form of packaging film. This is because cardboard can be used as protective material. It has lower environmental impacts than the present scenario in GWP, human toxicity and abiotic depletion for fossil fuels, as seen in Figures 4.6,4.9, and 4.10 However, it has higher values in acidification and eutrophication, as seen in Figures 4.7 and 4.8.

Cardboard should not have a problem with weatherproofing as the packaging plastic is often stored indoors at the construction site. As seen in Figure 4.6, there is a small difference between Cardboard and the present scenario, this is due to the fact that cardboard only replaces LDPE so it still has the same amount of PE, PP and, PS plastic at the construction sites. Only 21.95% of all the plastic at the construction site has been replaced. Since LDPE is not considered in some of the circular strategies it is therefore possible to combine Cardboard with other strategies for example Only PP.

5.3 Qualitative improvements

There are some circular strategies that could improve the circularity of the system. However, these are challenging to quantify, see Table 4.3 for the qualitative strategies.

Package re-purposing (ID-3) can extend the use of plastic packaging, by having another purpose when it has served its original use. A solution could be dismantling the product, enabling opportunities for other uses. However, this demands a lot of work for, planners, purchasers and suppliers and will probably have an effect on the circularity in the system.

Take back system (ID-5) is another way of increasing circularity by sending back the plastic products to the producers. The products can then be reused, thus decreasing the need for making new products. This strategy requires the producers to change their business models to accommodate the take back systems. External support in the form of laws and regulations might be necessary to implement the idea.

There are ways of reducing plastic usage by simple reducing the total amount of plastic used at the construction site (ID-8). The site visit showed that there were unnecessary amounts of plastic used which is not crucial for the purpose of the packaging and could be excluded from use. There is also double packaging used where different types of plastic and materials are combined. This makes it difficult or impossible to recycle and it could be forbidden to use making the system more recyclable (ID-14). To minimise plastic it is also possible to use Lightweight design packaging, which requires a different manufacturing method (ID-7). Although this requires engineering and more work for suppliers and it could be a difficult request from a single construction company to demand.

Coloured plastic is harder to recycle than transparent plastic. It needs special chemicals to separate the colour from the plastic, (Waste management company, personal communication, 4 February 2022). Therefore colour plastic should be avoided as much as possible (ID-13). The waste management company for the construction company provides LDPE plastic containers in different colour ratios. They have for example 100% transparent and 98% transparent. It is possible to demand suppliers to have transparent LDPE plastic (ID-12) or have a small logo so that the total amount of plastic does not exceed 2% colour, thus increasing the circularity. For the other plastic types, it's important to use as much transparent plastic that is physical as possible to make recycling easier. Another benefit of having more transparent plastic is economical profit as it is cheaper to recycle.

Same plastic (same utility) (ID-17), is a similar strategy to standardising and promotes easier sorting. Instead of standardising, that all products have the same plastic type the different stages at the construction site have the same plastic. When constructing for example the ground all plastic used at that time period should have the same plastic type. Later in the stages when constructing a kitchen, for example, it can contain a different plastic but all the plastic used at that time should consist of the same plastic type. This will make it easier for construction workers to sort plastic. In reality however, it will be hard to implement as it demands a lot of planning to decide which stage should have the different types of plastic. It will also be a problem for bigger constructions as they are in different construction stages at the same time.

Awareness programs (ID-19) can improve the existing plastic handling conditions at the sites by educating the people about the importance of sorting and taking up necessary actions to promote sorting. Construction companies should include the time needed for waste handling when creating timelines for the projects and also consider it as a part of

their organisational values.
Some of the plastic products present at the construction sites can be reused in other sites (ID-20). Products like buckets and liquid containers are kept idle after their initial purpose and thrown away eventually. Instead, they can be put to use at other construction sites prolonging their lifetime thus decreasing the need for new materials. The strategy can be difficult to visualise given that different sites might be at different stages of construction, vicinity of the sites and additional resources that might be required.
Multiple containers (ID-23) is about having multiple plastic collection containers on different floors at the construction sites which will improve the sorting in turn improve the recycling rates. This strategy might be difficult to implement in real scenarios because of many practical reasons at different construction sites for example lack of space to put the container.
The above mentioned circular strategies are possible to combine with each other and also the selected strategies to improve the circularity of the system more than choosing one strategy.

5.4 Setbacks

Some of the setbacks that were observed during the project were the lack of relevant data to assess total amount of packaging plastic and the total amount of different plastic types present in different waste containers. Due to the lack of uniformity in data collection, data from the regional and global sources were mixed when conducting MFA and LCA.
Research reports on the plastic in the construction sector from various reliable cross refer the findings from the 9 sample tests performed at different recycling centres in Sweden Edo et al. (2019). The quantities might differ making the data not representing the present situation.

5.5 Further research

As mentioned in setbacks there is no specific data for the construction company that was investigated in this report. General data for the research makes the result more unreliable. To get more data suppliers should state what type of plastic and quantities entering the construction sites and also waste management companies could measure the quantity of plastic that is waste handled. There is also an opportunity to quantify qualitative strategies in LCA but this requires further research in data.
There should also be more site visits to fully understand the plastic flow but also the research should start from the beginning of the project until the finished building. This because the different stages of a construction uses different amount of plastic.
Large construction stakeholders in Sweden should co-operate and decide on strategies together. This will make it easier for suppliers as they will provide with the same plastic to all construction companies. Furthermore it will help waste management companies as they also take care of the same plastic regardless of construction site.

6
Conclusion

The project has identified the problems with packaging plastic in the construction sector, by performing literature reviews, data collection, stakeholders interviews and site visits. The first result was a MFA study on construction sites in Sweden for a construction company. An MFA showed the amount of packaging plastic that was incinerated and recycled as well as which type of packaging plastic was present at the construction site. The recycling of packaging plastic was in the worst case scenario 5.8% and in the best case scenario 40%. From the result, it was clear that there was a potential of reducing the environmental impacts of packaging plastic.

To reduce the environmental impacts, circular strategies were applied. The strategy ideation used the seven design principles, adapted to circular economy. The strategies undergo a screening process to find the strategies that improve circularity the most. Furthermore, the strategies that had potential were investigated further through LCA. The results showed that there were strategies that could lower the environmental impact of packaging plastic. However, the strategy (ID-9) with Only PP plastic had the lowest amount of environmental impact compared to the BAU case having 974% more emissions and it is possible to implement it as it does not increase the workload for the construction workers or the waste management company.

It is possible to other circular strategies, for example, Only PE instead of Only PP because PE is widely used at the construction site making it easier for suppliers to shift plastic types. Cardboard packaging, Take back system, different longevity strategies with repurposing, sharing and reusing plastic and lower or changing transportation method is also an approach to lower the environmental impacts.

To conclude there are strategies that makes the construction sector more circular, they are impactful on different levels. However, all circular strategies that passed the first screening test can make the construction sector in Sweden more circular.

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A

Appendix 1

Table A.1: Initial list of circular strategies

7 Design principle
Modularisation:
1. LDPE plastic is used for every packaging plastic. (For some application a lot more plastic will be used, however it is easier to recycle)
2. Buckets or liquid containers will have the same function. The paint buckets are used as normal buckets after its initial use with storing paint with a wash in between.
3. Niche packaging repurposing. For example cable coil packaging has another purpose when it's done storing cables.
4. Reuse PP band to wrap LDPE bails.
5. Tack-back system. Send back the packaging to plastic product manufactures for them to be cleaned and reused again.
6. Reuse jerry cans, wash them and use them again.
Lightweight design
7. Have lightweight design in the packaging with different manufacturing methods, i.e Honeycomb, hollowed, or additive manufacturing.
8. Reduce the total amount of plastic. Don't use double protection.
Material Selection
9. Less plastic types. For example use PE instead of PP, With less variety comes easier recycling.
10. PLA, use bioplastic.
11. Use wood Packaging or Cardboard packaging instead of plastic.
12. LDPE (transparent or 98/2 colour percentages). LDPE is easy to recycle however painted LDPE is much worse, therefore only 2% coloured allowed for eg.
13. Use as much transparent plastic as possible.
Function Sharing
14. No double packaging for coils (LDPE and plastic coil wraps).
15. One garbage container on every floor (divide the container into multiple parts)
16. All containers are function sharing. Everything is in one container and sorted at the recycling plant.
Servitization
17. Standardising (use same plastic type at the same time for easier recycling for the workers)
18. The same plastic type for the same purpose, for example, all doors are the same plastic, or all buckets are the same plastic so it is easier for the construction workers to recycle .
19. Awareness programs at the site locations (DO and DON'Ts)
20. Sending the buckets (or other products) to other construction sites

(to prolong the use life of the products).
System Consideration
21. Electric trucks for transportation.
22. Less transportation (have packaging plastic production and construction material suppliers from the same place to lower the transportation distance.
23. Multiple containers for each type of plastic.
Longevity
24. Reusing the plastic products (one example is to reuse the nail gun magazines).
25. Design for repurposing the products.

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