A Comparative Life Cycle Assessment of Alternative Polymers to Poly(vinyl chloride) for Use in Flooring Applications

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Abstract

Poly(vinyl chloride) has a long history of use in the flooring industry. Throughout the years, several environmental and health issues have arisen concerning the production, usage and disposal of PVC. Forbo Flooring Systems is a company striving to provide environmentally friendly products for their customers, and therefore has an investigation of alternative polymers to PVC been initiated. The aim of this study is to investigate the environmental effects of the production of alternative polymers to PVC. The study consists of two main parts:

- A literature research in which potential alternative polymers were selected for further investigation based on qualities required in flooring applications.
- A life cycle assessment where the alternative polymers environmental impacts were evaluated using S-PVC as benchmark.

In the literature study, four alternative polymers were found: modified poly(phenylene ether) (mPPE), epoxidized linseed oil (ELO), ethylene methacrylic acid (EMAA) and ethylene vinyl acetate (EVA). The LCA results showed that PVC had the lowest environmental impact of the five different polymers. In the LCA study a dominance and a sensitivity analysis were also performed. The results of the dominance analysis were applied in the sensitivity analysis to evaluate the influence of the origin of the raw material and the energy. The sensitivity analysis revealed that the exchange of fossil-based to bio-based raw materials decreased the global warming potential of the polymer production but had an increase in other impact categories. It also determined that the exchange of generic European to Swedish electricity had a positive effect on the environment. The conclusion was reached that the production of PVC has a lower environmental impact than the investigated polymers. However, when bio-based raw materials and Swedish electricity was used for mPPE (PS), EMAA and EVA, the GWP was lower than for PVC. This indicates that the polymers have the potential to be an environmentally preferable alternative to PVC.

Sammanfattning

Poly(vinylklorid) har länge använts i golvindustin. Genom åren har flera miljö- och hälsoproblem framträtt för produktionen, användandet och avfallshanteringen av PVC. Forbo Flooring Systmems är ett företag som strävar efter att tillhandahålla miljövänliga produkter för deras konsumenter, därför har en undersökning av alternativa polymerer till PVC inletts. Syftet med denna studie är att undersöka miljöpåverkan från produktionen för alternativa polymerer till PVC. Studien består av två delar:

- En litteraturstudie där potentiella alternativa polymerer valdes för vidare undersökning baserat på kvalitéer som krävs för golvapplikationer.
- En livscykelanalys där de alternativa polymerernas miljöpåverkan utvärderades där S-PVC användes som riktmärke.

I litteraturstudien hittades fyra alternativa polymerer: modifierad poly(fenyleter) (mPPE), epoxiderad linfröolja (ELO), etylen-metylakrylsyra (EMAA) och etylen-vinylacetat (EVA). LCA resultaten visade att PVC har lägst miljöpåverkan av de fem olika polymererna. I LCA-studien utfördes en dominansanalys och en känslighetsanalys. Resultaten från dominansanalysen användes i känslighetsanalysen för att utvärdera påverkan av råvarornas och energins ursprung. Känslighetsanalysen visade att utbytet av fossilbaserade råvaror till biobaserade minskade den globala uppvärmingspotentialen för produktionen av polymererna men det ledde också till en ökning i andra kategorier. Den visade också att ett utbyte av generisk europeisk elektricitet till svensk elektricitet hade en positiv påverkan på miljön. Slutsatsen drogs att produktionen av PVC har en lägre miljöpåverkan än de andra undersökta polymererna. Dock blev GWP lägre för mPPE (PS), EMAA och EVA än för PVC när biobaserade råvaror och svensk elektricitet användes. Detta indikerar att polymererna har potential att bli ett miljövänligare alternativ till PVC.

Preface

This Master thesis was conducted during the spring of 2021 as a final part of our degree in Chemical Engineering at Lund University, Sweden. The thesis has been conducted on behalf of Lund University and Forbo Flooring AB. This thesis has also been a collaboration between the two students, Caroline Almqvist and Pernilla Larsson. The investigation of ELO and EMAA, the completeness and consistency check and the handling of GaBi-software has been performed by Caroline. Pernilla has overseen the investigation of mPPE (PS) and EVA, the LCA methodology and the sensitivity analysis. However, all results have been processed and discussed together.

We would like to express our sincere gratitude to our supervisor at Forbo Flooring Systems Jonas Rothén who initiated this project and has guided us throughout this whole process. We would also like to thank Floris Zeitler, Arjen Roelofs and Wido Levering for taking your time to answer our many questions. Lastly, we would like to thank our supervisor Baozhong Zhang and examiner Patric Jannasch at the Centre for Analysis and Synthesis for the feedback and guidance you provided.

Lund, June 2021

Caroline Almqvist　　　　Pernilla Larsson

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Abbreviations

ADPE	Abiotic depletion potential elements
ADPF	Abiotic depletion potential fossils
AP	Acidification potential
DBA	Dibutylamine
DCM	1,2-dichloromethane
DMBA	Dimethylbutylamine
DMP	2,6-dimethylphenol
EDC	1,2-dichlorethane
ELO	Epoxidized linseed oil
EMAA	Ethylene methacrylic acid
EP	Eutrophication potential
EPD	Environmental product declaration
ETP	Ecotoxicity potential
EVA	Ethylene vinyl acetate
FAETP	Freshwater aquatic ecotoxicity potential
GWP	Global warming potential
HMDA	Hexamethylenediamine
HTP	Human toxicity potential
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
LDPE	Low density polyethylene
MAA	Methacrylic acid
MAETP	Marine aquatic ecotoxicity potential
mPPE (PS)	Modified poly(phenylene ether) with polystyrene
ODP	Ozone layer depletion potential
PA	Polyamide
PLA	Polylactic acid
POCP	Photochemical ozone creation potential
PP	Polypropylene
PPE	Poly(phenylene ether)
PS	Polystyrene
PU	Polyurethane
PVC	Poly(vinyl chloride)
S-PVC	Suspension poly(vinyl chloride)
E-PVC	Emulsion poly(vinyl chloride)
TETP	Terristric ecotoxicity potential
VA	Vinyl acetate
VCM	Vinyl chloride monomer
VOC	Volatile organic compound

1. Introduction

1.1 Background

The global environmental crisis that the world is facing demands rapid changes in the society that we are living in today. In line with the Paris Agreement that entered into force in 2016, the Swedish government presented a plan of action to adapt to a circular economy as a part of reaching the Sustainable Development Goals in the 2030 Agenda.[1] [2] Many industries of today are thereby facing huge challenges to fulfill the aims of a circular economy. None the least the flooring industry, in which is included in the sector of building and construction that is one of the largest contributors to climate change.[3]

There is a tremendous amount of different flooring products to choose from on the market nowadays with wide ranges of prices, qualities and esthetics. Which flooring system most customers tend to choose depends, not only on the application, but also the ease of the installation process and costumer habits and trends.[4] Poly(vinyl chloride) floorings are a hugely debated topic due to the many environmental and health issues related to PVC production and waste treatment. It has therefore in recent years become an increased customer demand for non-PVC plastic flooring systems as awareness amongst the costumers has spread. To maintain relevance in the future of the flooring industries, companies need to adapt to the new demands of environmentally friendly products from the costumers, but also adapt to the restrictions of legislations and guidelines of the government.

In this study the environmental load of potential alternative polymers to PVC will be investigated. Focusing on polystyrene modified poly(phenylene ether) (mPPE (PS)), epoxidized linseed oil (ELO), ethylene methacrylic acid (EMAA) and ethylene vinyl acetate (EVA).

1.2 Purpose and research frame

The aim of this Master thesis is to investigate the environmental impact of four different polymers using Life cycle assessment (LCA) as a tool and suspension PVC (S-PVC) as the benchmark. These alternative polymers will be found through literature research and selected based on characteristics associated with flooring products. The polymers in focus are mPPE (PS), ELO, EMAA and EVA. The long-term goal is to find a replacement for the PVC in flooring systems with a more environmentally friendly alternative.

The research questions this thesis aims to answer are:

- Is any of the alternative polymers environmentally preferable to PVC?
- What are the alternative pathways of the production lines that can improve the environmental performance of the polymers?
- Does bio-based PVC have a lower environmental impact than fossil-based PVC?
- How would the improved pathways of the polymers compare to fossil-based PVC and bio-based PVC?

1.3 Forbo Flooring Systems

Forbo Flooring Systems is a global company, today situated in 36 different countries, that started off as a linoleum floor producing company in the late 19th century in Swedish Värmland. They provide their customers with a broad assortment of primarily linoleum, vinyl and textile flooring systems. At Forbo Flooring Systems, they have a vision of being a global leader in commercial floorings by creating sustainable solutions with innovative products for their customers.

Sustainability is a high priority for Forbo Flooring Systems which becomes clear with the smallest investigation of the company. They were one of the first companies in the world to provide complete life cycle assessments for all their products. Forbo Flooring Systems' linoleum flooring system called Marmoleum, has long been their main source of revenue, and the weighted average of their Marmoleum floors is CO_2-neutral (cradle-to-gate). It is also claimed to be biologically decomposable which makes it an environmentally friendly alternative. However, even though linoleum floors may be preferred in a global warming perspective there are applications where the qualities of the linoleum flooring system are inadequate. Forbo Flooring Systems has a variety of vinyl floorings with different characteristics and qualities, thus providing a range of application possibilities. [4,5]

1.4 Vinyl flooring

In the early 1930's the first commercially produced PVC products were found on the market. Owing to the practicality of these products, the market started to rapidly expand. In the 1940's and 1950's the PVC flooring became a popular alternative to the traditional linoleum due to its excellent characteristics and has ever since held a large share of the world flooring market.[6] Vinyl flooring is used when durability is a priority. It can withstand tough environments and heavy loading conditions. The lifetime of a vinyl flooring is predicted to be at least 10 years and up to 30 years. [6,7] Furthermore, PVC flooring can give waterproof and soundproof solutions, and it also requires low maintenance and has excellent cost effectiveness. PVC is therefore a superior choice especially in buildings with large spaces, heavy traffic areas and wet rooms. Yet, PVC has attracted a bad reputation of being a hazard to both the environment and human health, and not without reason. [6–8] The concerns regarding PVC production are many. In section *2.5.2 PVC disadvantages* the main concerns of PVC will be discussed.

2. Theory

2.1 Life Cycle Assessment

Life cycle assessment (LCA) is a tool used to investigate the environmental impacts of a product during its lifetime. There are different models that could be used when a lifecycle of a product is defined. A *cradle-to-grave* analysis considers all the stages a product goes through, from extraction of raw materials, production, usage and finally disposal. A *cradle-to-cradle* model is a version of cradle-to-grave, referred to when a circular economy is applied. In this, the waste and disposal phase are replaced with a recycling process in which the material is useful in new product. The third method is the *cradle-to-gate* analysis, which consider the extraction of raw materials and production of the product, but does not include the transportation to installation, installation, usage and disposal of the final product.[9,10]

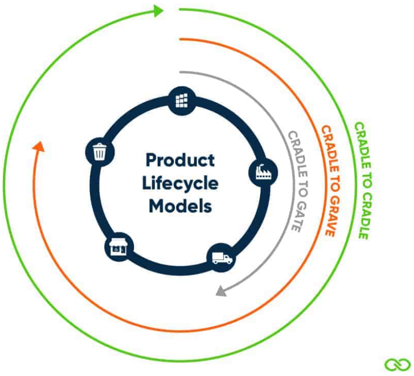

Figure 1: Sketch of the life cycle assessment models cradle-to-gate, cradle-to-grave and cradle-to-cradle.[11]

The structure and procedure of an LCA is described by ISO standard 14040 series[12]. It consists of four phases, Goal and Scope definition, Life Cycle Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation *Figure 1*. Firstly, *the goal and scope* are defined by describing the purpose and boundaries of the analysis. It should include a definition of the system, the functional unit, the impact categories that will be used and the rules that will be followed in the analysis. In the *lifecycle inventory analysis* (LCI) the data for all processes is procured and necessary estimations and calculations are performed. The data is then sorted and calculated in the *life cycle impact assessment* (LCIA). The environmental load is translated to impact in accordance with the characterization method of choice. Lastly, the *interpretation* of the results is made. This section includes definition of significant issues and checks of the completeness, consistency and sensitivity of the results. It should also include a conclusion of the study and recommendations for the future. [9,10]

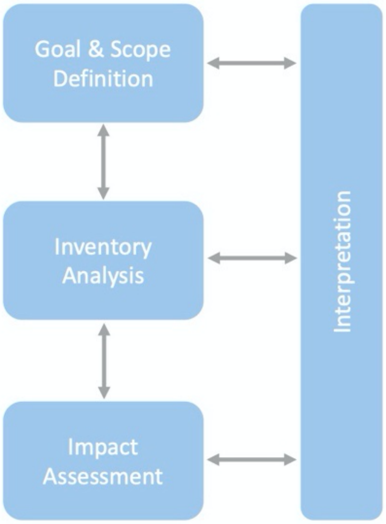

Figure 2: Description of the LCA work process based on ISO standard 14044: 2006.

The work process of an LCA study is iterative, meaning that the definitions made in the goal and scope outlines the rest of the study. Thus, depending on the outcome of the results in later steps, the initial goal and scope may need adjusting to the findings. (*Figure 2)*

In section *4. Life Cycle Assessment* detailed description is made for the LCA-process for the different polymers investigated in this study.

2.2 Polymer flooring systems

In this report, a homogeneous vinyl flooring that Forbo offers on the market today, called Sphera, will be the benchmark for the qualities needed in a polymer used in flooring systems. Sphera is appropriate for use in both wet rooms and commercial facilities. It is often used in healthcare facilities because of its excellent properties. Sphera has good durability and high resistance to wear, cuts and stains. It is possible to weld the seams of the tiles, this keeps germs, dirt and moisture out of the floor. Sphera consists of two layers, seen in *Figure 3,* first a compact PVC layer and then a PU lacquer. The PU lacquer provides a surface that makes it easier to clean and maintain the flooring, it also enhances the protection against scuffing, scratching and staining. [13]

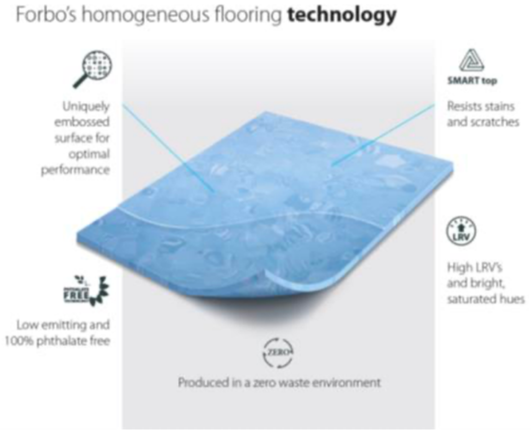

Figure 3: Forbo Flooring Systems' homogeneous vinyl flooring system Sphera.[13]

The first step in the manufacturing of Sphera is the making of PVC chips. These are produced by making a vinyl mass from PVC dry blend and color pigments. The vinyl mass is then pushed through a die plate which creates chips in the desired shape. The chips are then placed onto a conveyor belt and by using a steel-belt press the sheet is made. Lastly, the PU lacquer is applied whereupon the material is first heated and then slowly cooled down to release the tension in the product which results in a more dimensionally stable product. The PVC layer consists of a mix between PVC and different additives and stabilizers. [13]

2.3 Criteria for polymers used in flooring

It is hard to determine from the properties of a polymer if it would function in a flooring product. Usually, additives and fillers are required which influence the properties of the material significantly. Depending on the application of the floor, the properties needed for the polymer changes. However, in common for all polymeric floorings is that the polymer needs to have good processability, this means that the viscosity and the temperatures should be suitable for the processing technique used. Another important property is that it needs to have good chemical resistance to acids and bases to withstand harsh environments. Other important properties are that it should be UV resistant, mechanical stable and resistant to oxidation, it also needs to be flexible for installing purposes. For a wet room flooring that can be used in commercial facilities it is important that the polymer has a low water absorptivity and that the floor can be welded together to ensure that no water can penetrate. [14,15] To some extent additives can adjust for lacking desirable properties of the polymers. Although, this has to be determined experimentally.

2.4 Literature study of polymer selection - Method

The selection of alternative polymers to PVC, interesting for use in flooring systems, was conducted based on a literature study. The database LubSearch was used for gathering relevant journals, articles and books regarding the subject. One criterion for the academic journals to be considered relevant was that they should be peer reviewed.

Since no experiments have been able to be performed during this thesis the main criterion for the selection of the polymers has been that previous studies conclude that the polymers functionality in flooring applications is deemed appropriate. This applies to polymers that have been evaluated in flooring applications in academic articles, polymers that have been used in commercial floorings and polymers used as alternatives to PVC in applications where the polymer properties are similar to the requirements of flooring. The desired qualities of the polymers listed in *section 2.3 Criteria for polymers used in flooring* were all noted as advantages since the more qualities the polymer fulfills itself, the need for additives is assumed to be less. The literature study was concluded with a SWOT-analysis in which four polymers were selected for further investigation of the environmental impacts.

2.5 PVC

PVC, structure seen in *Figure 4*, is one of the most widely used plastics and is especially important in the building and construction industry due to its durability, ease of assembly and its cost effectiveness.[16] [7] According to Plastics Europe, an association of plastic manufacturers in Europe, the total production of PVC the year of 2019 was more than 5 million tons which represents about 10% of the total plastic production in Europe.[16]

PVC is a thermoplastic material and can be processed by the conventional plastic processing techniques such as extrusion, calendaring, injection and blow molding. There are two types of PVC, rigid and flexible. Rigid PVC is strong and hard and is unmodified, meaning there are no additional additives. Flexible PVC on the other hand contain additives, such as plasticizers, to make it soft and malleable. The flexible PVC has rubber-like elasticity and has high tensile and fatigue strengths. Flexible PVC is used in flooring.[9,17]

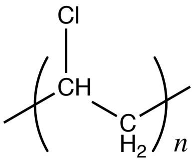

Figure 4: Chemical structure of PVC with n repeating units.

Because of the existing polar groups in PVC (the chloride group), it can easily be mechanically mixed with various substances, the so-called 'ease of formulation' characteristic. Plasticizers, additives and modifiers are added to PVC to design the required physical properties. This can improve flexibility, elasticity, impact resistance, anti-fouling, prevention of microbial growth, anti-misting and fire retardancy.[9,17]

2.5.1 PVC production

The production of PVC can be split into five parts: purification of ethylene, production of chlorine gas, synthesis of 1,2-dichlorethane (EDC), vinyl chloride monomer (VCM) production and finally polymerization of PVC. The compounds used are seen in *Figure 5*. Most often formulation or compounding is required with additives whereupon direct or end product processing is possible.

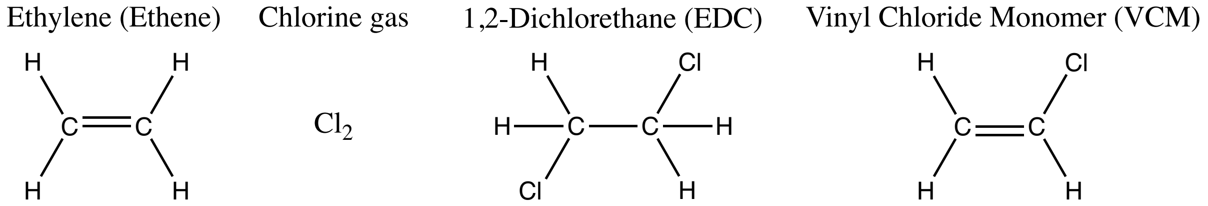

Figure 5: Chemical structure of the raw materials used in PVC production: ethylene & chlorine gas and the intermediate products 1,2-dichlorethane (EDC) and vinyl chloride monomer (VCM).

2.5.1.1 Ethylene production

Steam cracking

There are several different ways to produce ethylene commercially. The most common method is steam cracking, a high temperature pyrolysis (740-900°C, 2-4 bar). In this process the feedstock of saturated hydrocarbons is broken down into lighter hydrocarbons. The raw material used is crude oil or natural gas that undergoes a separation process whereupon the feedstock substances for steam cracking, such as ethane, propane, butene and naphtha, are secured. Due to the high temperatures during this process emissions of NO_x are released. [18,19]

Ethanol dehydration

Another commercially used method for ethylene production is ethanol dehydration. Ethanol can either be produced from biomass (bioethanol) through fermentation of sugar crops, lignocellulose or different types of starches, or through hydration of ethylene derived from petrochemical feedstock (synthetic ethanol). Thus, the ethanol used for bio-based ethylene production is bioethanol.

Production of bio-based ethanol always involves following four steps: feedstock treatment to receive a sugar solution, addition of yeast or bacteria to convert sugar into ethanol and carbon dioxide, distillation to separate the ethanol from the fermentation broth and finally, if required, dehydration. Important to note is that even though bioethanol is based on bio-based raw material, the final product is not carbon neutral due to CO_2 emissions from e.g., growing crops, harvesting and transportation.

As mentioned, synthetic ethanol can be produced by the hydration reaction of ethylene. The reversed reaction is the *dehydration* of ethanol to form ethylene. With this method a selectivity of over 99% can be achieved, which makes it a rather simple production process. Another advantage of bio-based ethanol is, beyond the advantage of the use of renewable raw materials, the reduction of NO_x and CO_2 emissions compared to the steam cracking process.[18–20]

2.5.1.2 Chlorine gas production

The chlorine industry plays a major part in the production of PVC. In the year of 2019, over 30% of the chlorine produced in the EU had its end use in PVC which thereby was the second largest application of chlorine after Isocyanates and oxygenates.[21]

Chlorine gas (Cl_2) is mostly synthesized from sodium chloride (NaCl) by high-energy electrolysis called the chlor-alkali process where the sodium chloride is usually mined from underground salt solution deposits. There are three methods applied in industry using the chlor-alkali process: mercury cell electrolysis, diaphragm cell electrolysis and membrane cell electrolysis. [22,23] All three methods are based on electron transfer from the anode to the cathode by interchange of ions and the applied current with the overall reaction (1).

The overall reaction: $2NaCl\,(aq) + 2H_2O \rightarrow Cl_2 + H_2 + 2NaOH(aq)$ (1)

Cathode: $2H^+ + 2e^- \rightarrow 2H_2$ (2)

Anode: $2Cl^- \rightarrow Cl_2 + 2e^-$ (3)

The coproducts from this process are hydrogen gas (H_2) and sodium hydroxide solution (NaOH (aq)) which are important products in a number of different industries such as construction, textiles, paper and cleaning. [22,24,25]

2.5.1.3 Synthesis of 1,2-dichlorethane (EDC) and Vinyl Chloride Monomer (VCM)

There are a total of five main steps included in the production of VCM. (1) Direct chlorination of ethylene to EDC, (2) oxychlorination of ethylene to EDC from recycled HCl and oxygen, (3) purification of EDC, (4) pyrolysis of EDC to form VCM and finally (5) purification of VCM.[3,26] According to J. Dry, et.al. (2003) about 95% of the world production of VCM uses a so-called balanced process that could be described with following reactions:

Direct chlorination: $CH_2 = CH_2 + Cl_2 \longrightarrow ClCH_2CH_2Cl$ (4)

Oxychlorination: $CH_2 = CH_2 + 2HCl + \frac{1}{2}O_2 \longrightarrow ClCH_2CH_2Cl + H_2O$ (5)

EDC pyrolysis: $2ClCH_2CH_2Cl \longrightarrow 2CH_2 = CHCl + 2HCl$ (6)

Since the hydrochloric acid is collected from the EDC pyrolysis it can be reused in the oxychlorination which makes equation 7 represent the overall reaction of the balanced process.

$$2\,CH_2 = CH_2 + Cl_2 + \frac{1}{2}O_2 \rightarrow 2CH_2C = HCl + H_2O \quad (7)$$

Small amounts of byproducts are formed from these reactions that include chloroethane, trichloromethane, tetrachloromethane, 1,1,2-trichlorethane, tetrachloroethane, carbon oxides and hydrochloric acid. Where 1,1,2-trichlorethane is the main byproduct. Traces of chlorinated aromatics can also be found e.g., dioxins. [26]

2.5.1.4 Polymerization of VCM

There are three different methods used for the polymerization of VCM industrially: suspension-, emulsion- and bulk polymerization in which suspension polymerization represents a major part of the world production of PVC. [27] The suspension polymerization is also the main method used for PVC production intended for flooring products. However, Forbo Flooring Systems uses both suspension PVC (S-PVC) and emulsion PVC (E-PVC) since they provide slightly different qualities.

Suspension polymerization

In suspension polymerization the polymerization process is carried out in small water droplets. Water-insoluble liquid vinyl chloride monomers (VCM) are dispersed in water through vigorous stirring creating the small droplets. A monomer soluble free radical initiator is also present in the water droplets, initiating the polymerization. The water droplets are stabilized against coalescence by a suspending agent that is a water-soluble polymer that increases the viscosity and reduces the movement of the monomer droplets. To achieve optimum morphology of particulate PVC, other additives are also employed. This way of production yields relatively big and porous particles between 0.1 and 0.2 mm.[17]

Emulsion polymerization

The emulsion polymerization also takes place in an aqueous solution with the difference that the reaction medium contains surfactants, the initiator used is water-soluble. The surfactants create a micellar structure in which the water-soluble initiator can enter and start the polymerization reaction whereupon PVC lattices are produced. However, the polymer obtained is very difficult to separate from the residual of the reaction which results in that the reaction mix is used as it is. Typically, the emulsion polymerization yields smaller particles that ranges between 0.2 and 3.0 μm.[17]

2.5.2 PVC disadvantages

As mentioned in section *1.1 Background*, there are many health and environmental issues associated with the production, usage and disposal of PVC products. In this section the major issues will be further discussed.

Chlorine

Emissions of chlorine gas during the production, transport or storage of chlorine has a significant negative effect on the environment if it occurs. The production of chlorine gas is a high energy demand process and therefore causes high emissions of CO_2 and SO_2 that are associated with global warming and acidification respectively.

Mercury

Up until the year of 2017 mercury cell electrolysis was used as a production method of chlorine gas. But already in the 1970's an increasing concern about the effect of mercury on the environment and in human health has caused a decrease in the number of mercury cell plants ever since. In Europe methods of protecting the environment from mercury were developed that greatly decreased the emissions of mercury to the atmosphere and wastewater during this time period. More recently, the mercury export ban regulation by EU in the year of 2015 ruled that the industry of chlor-alkali should be mercury free by the year of 2017 [28] and the mercury cell has therefore been faced out since then.[21,29] According to the *Euro Chlor Members* only 12 mercury plants are still operating within the World Chlorine Council[*] (2020)[30].

Dioxins & Volatile organic compounds (VOC)

Dioxins are a group of chemical compounds that are environmental pollutants in which some are highly toxic. In the manufacturing process of 1,2-dichlormethane (DCM) are dioxins emitted and are thus the main contributor to the total human toxicity potential (HTP) of the whole production of PVC. [31]

Volatile organic compounds (VOCs) are often associated with environmental pollution, even though not all VOCs are harmful. These compounds have a high vapor pressure at room temperature, resulting in a high volatility. The emissions of VOCs are strictly regulated by law. In Europe it is regulated by the *Directive on industrial emission*.[32] During the processing of crude oil emissions of VOC are released which causes photochemical ozone creation. [3]

Vinyl chloride monomer (VCM)

The monomer used to synthesize PVC was suspected to be toxic already before the 1930's when PVC was first commercially produced. VCM was discovered to cause fatty degeneration in the liver and kidneys to test animals. A number of other health issues have since then been discovered related to VCM including angiosarcoma, a rare type of cancer.[6,7] The industries answered by introducing a stripping process of the VCM left in the final products in a closed-looped system. This resulted in that in today's industries low levels of VCM in final products can be ensured (>1ppm) in S-PVC. [3,8]

Today the emissions associated with the production of DCM and VCM are not considered a great hazard due to the low emission levels and the fact that the substances are not stable in the environment. This owing to the modern facilities that can manage the emissions close to or below the level of negligible risk levels. [3]

Waste treatment and Recycling

According to the EU commission, the waste treatment of the chlorine containing residues does not have to have a high environmental impact if treated correctly in hazardous waste incineration plants. A small amount of dioxins and chlorine may be released. However, this is not the case if waste is landfilled instead of incinerated. [3] If PVC products are dumped on landfills contamination of the groundwater may occur due to leaking chemicals.

The recycling of PVC can be split into two categories: pre-consumer waste and post-consumer waste. PVC is in principle 100% recyclable; it only depends on the effectiveness of the prevention of contaminations. In pre-consumer waste, meaning the waste associated with the production and installation phase, a high recyclability is possible to achieve since it can be collected separately in

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[*] A global network of national and regional trade associations and their member companies representing the chlorine and chlorinated products industries.

defined qualities.[20] For example, at Forbo Flooring Systems the rejected material, cuttings and trimmings are being reused in the manufacturing process of their vinyl flooring products. [13]

In the case of post-consumer waste, the recyclability is much lower. Depending on the specific product in question, the waste can be more or less pure resulting in expensive separation processes. Consequently, recycled PVC has a low commercial value and thereby the recycling rates are limited.

Additives

PVC are normally formulated to achieve suitable properties for the application of the product. Additives such as softeners, stabilizers, fillers and pigments are most often used. A major reason for the bad reputation of PVC has been related with the discussion of stabilizers and softeners and the heavy metals and phthalates emissions associated with the use and disposal of these PVC products. A lot of restrictions, research and analyses have been conducted in this area that has resulted in improvement in environmental performances of these products. [3,8,20,31,33] This topic will however not be further discussed in this report.

3. Alternative Polymers to PVC

In this section four alternative polymers to PVC will be presented: modified poly(phenylene ether) (mPPE), epoxidized linseed oil (ELO), ethylene methacrylic acid (EMAA) and ethylene vinyl acetate (EVA). These four polymers have been found through literature research, all having interesting properties that may be suitable for flooring applications.

3.1 Modified Poly(phenylene ether) (mPPE)

Pure PPE is hard to use on its own due to its very high melting temperature and high melt viscosity, which makes it hard to process. PPE is also brittle and its resistance to organic solvents is poor. The properties can be enhanced by blending it with other polymers, such as PS, PA and PP, to create mPPE. PPE and PS are completely miscible at all concentrations. When PPE is blended with PS most of its properties remain but the processability is enhanced. Modified PPE is used in the electrical and automotive industries and for liquid transportation.[34] The focus in this report will be on PPE blended with PS. The structure of PS and PPE can be seen in *Figure 6.*

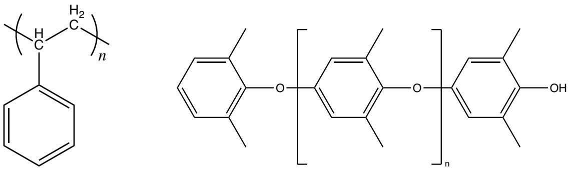

Figure 6: Chemical structure of polystyrene (PS), with n repeating units (left) and the chemical structure of PPE with n repeating units (right).

Modified PPE has been used instead of PVC in commercial cables. The company Alphawire is one of the suppliers of mPPE (PS) cables, and their product does not contain phthalates, halogen or heavy metals. Based on this, Alphawire claims that their mPPE (PS) is a greener alternative to PVC.[35]

The company Sabic produces mPPE (PS) under the name Noryl™. They make several different blends using different additives. One of those blends are PPE and PS. This is an amorphous blend and combines properties from both PPE and PS. It has low moisture absorption and low mold shrinkage, it offers good resistance to acids, bases and cleaning agents. The tensile, flexural and impact strength is high as well as the stiffness. It is possible to combine with non-halogen-based fire retardants. Because of their agreeable properties they can be used in many different applications.[36]

PVC has often been used in cables and polymers used in cables require similar properties to those used in flooring systems. The exception is that more flexibility is needed in the cables. This can be achieved by addition of more softeners.[4] This indicates that mPPE (PS) could be a good alternative for use in flooring products.

3.1.1 Poly(phenylene ether) (PPE)

Poly(2,6-dimethyl-1,4-phenylene ether) (PPE), also called poly(phenylene oxide) (PPO), is a linear, non-crystalline thermoplastic that is used for a wide range of applications because of its unique combination of properties. It has high strength, high heat distortion temperature and high chemical resistance as well as inherent flame resistance. Other properties of PPE are good dimensional stability, excellent electrical insulation properties and high mechanical properties.[34] PPE does not have any polarizable groups and no hydrolysable bonds, which make it hydrolytically stable with a low water absorption. It also has a high glass transition temperature, low density and low dielectric properties.[37]

3.1.1.1 Production of PPE

The production of PPE includes the production of the raw materials methanol and phenol, synthesis of the monomer 2,6-dimethylphenol and lastly a polymerization step to produce PPE.

Methanol production

Methanol can be produced from several different carbon feedstocks such as natural gas, coal, biomass and carbon dioxide. The most common way to produce methanol is from natural gas and it accounts for about 90% of the total methanol production. Methanol is produced by first producing syngas which is a mixture of H_2, CO and CO_2. The syngas is made from natural gas by steam reforming and autothermal reforming, this converts the methane to hydrogen, carbon monoxide and carbon dioxide by reacting it with oxygen and water. [38]

Steam reforming: $CH_4 + H_2O \rightleftarrows CO + 3H_2$ (8)

Autothermal reforming: $CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$ (9)

The syngas is later converted to methanol by hydrogenation of carbon monoxide and carbon dioxide at pressures between 50-100 bar and temperatures between 200-300°C. Methanol is purified by distillation. [38]

$$CO + 2H_2 \rightleftarrows CH_3OH \qquad (10)$$

$$CO_2 + 3H_2 \rightleftarrows CH_3OH + H_2O \qquad (11)$$

The process for producing methanol from biomass is similar to producing it from natural gas, first syngas is produced from biomass and then the syngas is synthesized to methanol and purified just as in the case from natural gas. The syngas is made from gasification of the biomass. [38]

Phenol production

Phenol is made from the cumene process, which turns cumene into phenol and acetone. Cumene is formed by alkylation of benzene with propylene together with an acid catalyst. There are several different ways to produce phenol from the cumene process, but the main reactions are the same. First cumene reacts with oxygen to form cumene hydroperoxide, this is a free-radical mechanism and is auto-catalyzed by the cumene hydroperoxide. The cumene hydroperoxide is later decomposed, by using an acid catalyst, to phenol and acetone. The process conditions are optimized to minimize the side reactions and it is therefore highly selective method to form phenol and acetone.[39]

Production of the monomer 2,6-dimethylphenol

2,6-dimethylphenol (DMP) is the monomer which is polymerized to make PPE. DMP can be made both in the liquid phase and in the gaseous phase. However, it is mostly produced in the gaseous phase due to some drawbacks in the liquid phase method such as long reaction times, high pressures and the necessity of separating the product from the catalyst and unreacted substances. DMP is carried out with different catalysts, e.g. oxides, mixed oxides or zeolites. Methylation of phenol is a strongly exothermic reaction that takes place at temperatures around 330°C. A fluidized bed catalyst can be used to maximize the catalyst surface and to have good temperature control. The fluidized catalyst bed also leads to good heat and mass transfer.[40]

Polymerization of PPE

2,6-dimethylphenol (DMP) can be polymerized to PPE by oxidative coupling. This results in a linear polymer when DMP is coupled through carbon-oxygen coupling. Though, a carbon-carbon coupling can also take place which will result in formation of diphenoquinone. Yet, under the right reaction conditions this will only be a small amount. The polymerization is an exothermic process and can proceed at room temperature and atmospheric pressure. The catalysts used are copper with amines used as ligands. The different amines require different ratios to copper for the optimum polymerization. The polymerization behaves like a step growth polymerization where water is formed as a coproduct. A non-polar solvent like toluene is used. [41]

3.2 Epoxidized linseed oil (ELO)

Epoxidized linseed oil is a polymer that has received some attention in later years as the demand for polymers derived from renewable resources increases. Vegetable oils are known to be a good raw material for synthesis of polymers especially used for adhesives and coatings. ELO is commercially available from several different suppliers. The structure of ELO is presented in *Figure 7.*

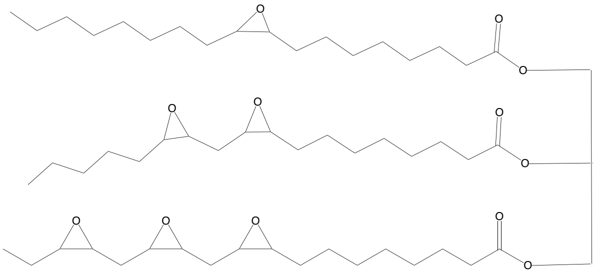

Figure 7: Chemical structure of epoxidized linseed oil (ELO).

To sustain polymers with high stiffness, that is more suitable for e.g., flooring systems, a high crosslinking density is required of the polymer. To achieve this, the most unsaturated vegetable oils, such as linseed oil and soybean oil, must be used. A crosslinker is also necessary to achieve a solid structure of the polymer. In a study conducted by D.T. Carter et. al (2008), ELO has been investigated as a possible alternative polymer to PVC used in flooring applications using a maleic monoester as the crosslinker, seen in *Figure 8*. The findings were that the cured ELO material may have comparable performance to that of PVC tiles in a flooring application. [42]

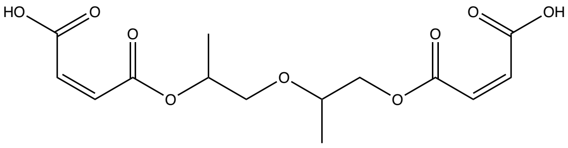

Figure 8: Chemical structure of the maleic monoester used as the crosslinker in the curing of ELO.

3.2.1 Production of ELO

The manufacturing process of cured or crosslinked ELO can be divided into three parts: Production of ELO, synthesis of crosslinker and curing of ELO.

Synthesis of ELO

The synthesis of ELO is achieved through epoxidation of linseed oil using hydrogen peroxide and acetic acid together with a solid catalyst in a solvent-free environment. The linseed oil is extracted from agricultural flax plants.

Production of Crosslinker

The crosslinker considered in this study is the maleic monoester, used in the article by D.T. Carter et. al (2008)[42], synthesized from maleic anhydride and dipropylene glycol. This is done over nitrogen atmosphere at a constant temperature around 95°C. Since it is an exothermic reaction, the vessel is initially heated whereafter cooling is required.[42] The maleic anhydride is produced through oxidation of n-butane and the dipropylene glycol is produced by hydration of propylene oxide in aqueous steam. [43,44] In a study by Gonzales-Garay et. al (2017) a method for production of propylene glycol from the biodiesel byproduct glycerol was presented.[44] This is a highly interesting alternative bio-based pathway for the production of dipropylene glycol.

Curing of ELO

The final step is the curing of ELO. This is done by simply mixing the crosslinker with the ELO. In room temperature, this will take a matter of days, but by increasing the temperature the reaction time will decrease.[42]

3.3 Ethylene Methacrylic Acid (EMAA)

Ethylene methacrylic acid is a copolymer of the monomers ethylene and methacrylic acid (MAA) that were first discovered in the 1960's, *Figure 9*. The MAA content can vary between 4 and 20 wt% and the crystallinity is between 33 and 37%.[16] The acronym used throughout this report is EMAA but it also goes under the acronym PEM. EMAA is a polymer with the outstanding properties of inherent flexibility and self-healing properties.[16] This is very attractive attribution in an additive for improving durability of brittle polymers and polymer composites.[17] Applications common for EMAA thereby includes adhesives, footwear, different coatings and films as well as wires and cables,[16] but it is also known to have been used in flooring products.

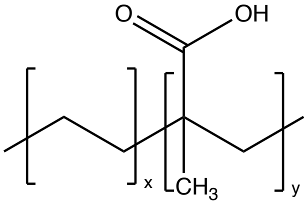

Figure 9: Chemical structure of EMAA. The molar ratios of ethylene and MAA monomer are represented by x and y respectively.

3.3.1 Production of EMAA

The production of EMAA can be divided into three parts: Production of methacrylic acid, production of ethylene and the polymerization of EMAA. The production of ethylene is described in *2.5.1.1 Ethylene production.*

Methacrylic acid production

The first step in the production of methacrylic acid is the synthesis of hydrogen cyanide (HCN). This is done by reacting ammonia with methane in high temperatures (>1000°C) in a process called Andrussow process. The ammonia used is synthesized through the Haber-Bosch and the methane originates from natural gas. A coproduct is also formed in this process, ammonium sulphate. In the second step, the hydrogen cyanide is reacted with acetone in the presence of a basic catalyst to produce acetone cyanohydrin. Acetone is most commonly produced from the cumene process in which cumene, synthesized from benzene and propene, is oxidized to form acetone and phenol. In the third step, the cyanohydrin is first reacted with concentrated sulphuric acid to form the intermediate methacrylamide acid sulfate, whereupon the intermediate is hydrolyzed with an excess of water to form methacrylic acid (MAA). A coproduct of ammonium sulfate is also formed. If instead the methacrylamide acid sulfate is hydrolyzed using aqueous methanol a mixture of methyl methacrylate and methacrylic acid is formed.

Polymerization

The final step of the production of EMAA is the copolymerization of ethylene and methacrylic acid. The polymerization of EMAA is performed under similar conditions as the LDPE polymerization.

It is synthesized by a free radical polymerization using a tubular or a stirred autoclave reactor. It requires high temperatures and pressures, often above 200°C and 2000 bar.[45]

3.4 Ethylene Vinyl Acetate (EVA)

Ethylene vinyl acetate is a thermoplastic random copolymer of ethylene and vinyl acetate (VA), the structure can be seen in *Figure 10.*[46]

Polyethylene is not a polar compound. This prevents it from being used in several applications because it is often not compatible with other materials, such as fillers and other polymers. It also decreases the dyeability and adhesion. These properties are enhanced when ethylene is polymerized with a polar comonomer, such as vinyl acetate. The composition in EVA varies, up to 40 wt% is VA-content.[45] The polyethylene forms crystalline segments, but with increasing VA-content the crystallinity decreases due to the fact the VA interfere with the crystalline segments.[46] The properties of EVA therefore depend greatly on the VA-content.

EVA has a wide range of commercial applications. It is used as flexible packaging, footwear, adhesives, cables, for biomedical applications[46] and in the automotive industry.[45] It has also been used in flooring systems.

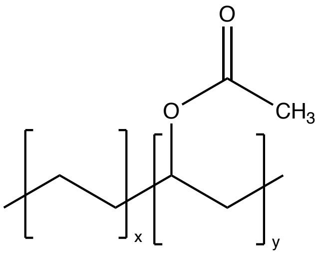

Figure 10: Chemical structure of EVA. The molar ratios of ethylene and vinyl acetate monomer are represented by x and y respectively.

3.4.1 Production of EVA

The production of EVA includes the production of the two monomers ethylene and vinyl acetate, and the copolymerization of EVA. The ethylene production has been described in section *2.5.1.1 Ethylene production*.

Vinyl acetate production

The vinyl acetate monomer is produced in a gas phase reaction by ethylene, acetic acid and oxygen on a catalyst bed. Water is also formed in the reaction as a byproduct. Carbon dioxide is formed as a side product since the selectivity is not 100% and some of the ethylene is combusted. [47,48] The pressure is usually between 5-12 atm and the temperature between 140-180 °C.[48] There are different processes to produce acetic acid but the most common one for large-scale production is carbonylation of methanol. When methanol and carbon monoxide react, acetic acid is formed. The process requires high temperatures and pressures.[49]

EVA copolymerization

The polymerization of EVA is performed under similar conditions as the LDPE polymerization. It is synthesized by a free radical polymerization using a tubular or a stirred autoclave reactor. It requires high temperatures and pressures, often above 200°C and 2000 bar.[45]

4. Life Cycle Assessment

4.1 Goal

It has long been known that PVC floorings have a negative impact on the environment, and not to mention the toxicity to both humans and the ecosystems from the emissions from the PVC industry. At Forbo Flooring Systems alternatives to PVC flooring want to be explored to meet the environmental goals of the Paris agreement and the ambitions of a circular economy in Sweden.[1,2] As to evaluate the environmental impacts of alternative polymers to PVC, life cycle assessments will be performed on mPPE (PS), ELO, EMAA and EVA using fossil-based S-PVC as the benchmark.

The goal of this LCA study is to evaluate the environmental impact of the alternative polymers to PVC in order to determine any possible gain from an environmental point of view if PVC was replaced with any of the alternatives.

4.2 Scope

4.2.1 System

This LCA will be a cradle-to-gate analysis of the polymers mPPE (PS) ELO, EMAA and EVA using S-PVC as the benchmark. This means it will cover the production of the polymers from raw material extraction to the production of the chemicals, and finally the polymers. A general description of the system boundary is presented in *Figure 11*.

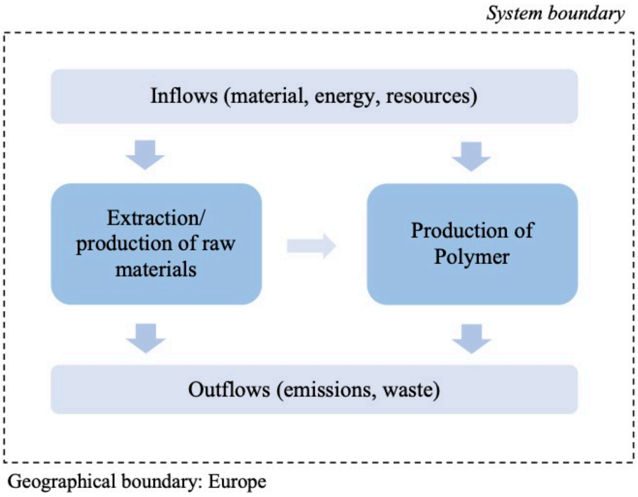

Figure 11: Description of the system boundary for the LCA.

Additives, softeners and fillers that are commonly used in flooring systems are outside the scope of this study. Transportations of the materials between the production sites will not be included for these processes since the transportations are assumed to have minor climate impact compared to the other stages in the LCA, supposing that the production sites of the raw materials are located in

Europe. The equipment e.g., laboratory equipment will neither be included, nor will the accidental environmental effects. Circulation of the flows, i.e., catalysts, inert gas and solvents, will not be performed. Separation and purification steps have not been included, neither have process water.

4.2.1.1 Functional unit

The functional unit is determined as 1 kg of produced polymer. The LCA will only cover the production of the polymer (cradle-to-gate) and not the use phase or the disposal of a final product. Therefore, no reference time will be used. The intent of this study is to evaluate the polymers value in a flooring system, but since the amount of polymer needed per 1 m^2 of flooring product cannot be known at this stage the functional unit is determined to be 1 kg.

4.2.1.2 Geographical and temporal system boundaries

The geographical system boundary is set to Europe where Forbo Flooring Systems has their production sites and their main share of revenue. This is also where the polymers are assumed to be produced since no specific producer is considered. The LCA will be constructed for how the polymers are currently produced and the data gathered should therefore be as new as possible. It has thus been decided that the gathered data should not be older than 10 years.

4.2.1.3 Product systems

S-PVC product system

The system boundary of S-PVC production, described in *Figure* 12, includes the production of chlorine gas (Cl_2), production of dichlorethane (EDC), production of vinyl chloride monomer (VCM) and suspension polymerization of S-PVC. It also describes the origin of the raw material using the color combination:

- green: non-fossil based raw material
- red: fossil-based raw material

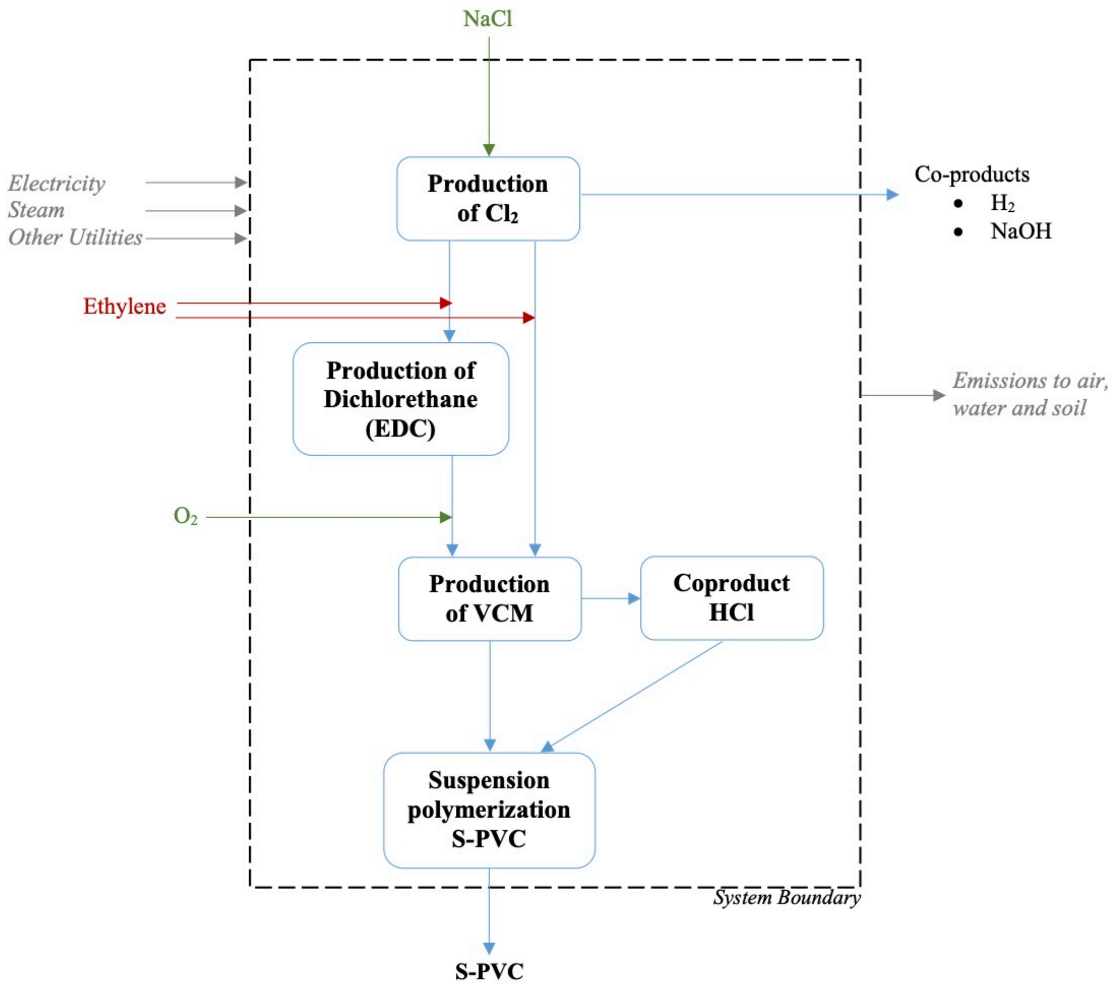

Figure 12: System boundary for the production of S-PVC. The red arrows indicate a fossil-based raw material, the yellow ones indicate fossil- or bio-based raw material and the green indicates a non-fossil-based raw material. The dotted line shows the system boundary.

The production method for chlorine accounted for in this LCA is country specific for Germany and is therefore an average of the two methods (diaphragm and membrane) compiled there. The chlorination step of ethylene included in this system results in about 50% direct chlorination to form vinyl chloride monomer (VCM). The rest of the ethylene undergoes oxychlorination to dichloroethane (EDC). The EDC is then treated in a cracking furnace to form vinyl chloride monomer (VCM). The coproduct HCl is recirculated and used in the suspension polymerization step.

mPPE (PS) product system

The system boundary for mPPE (PS) production can be seen in *Figure 13*. It describes the production steps of polystyrene (PS) which includes the synthesis of ethylbenzene, styrene production and the polymerization of PS. It also describes the production of PPE which includes the production of methanol, phenol, 2,6-dimethylphenol (DMP) and lastly the polymerization of PPE. The final step within the system is the blending of PPE with PS to form mPPE (PS). The product system described in *Figure 13* also defines the origin of the raw material according to the color combination:

- Green: non-fossil based raw material

- Red: fossil-based raw material

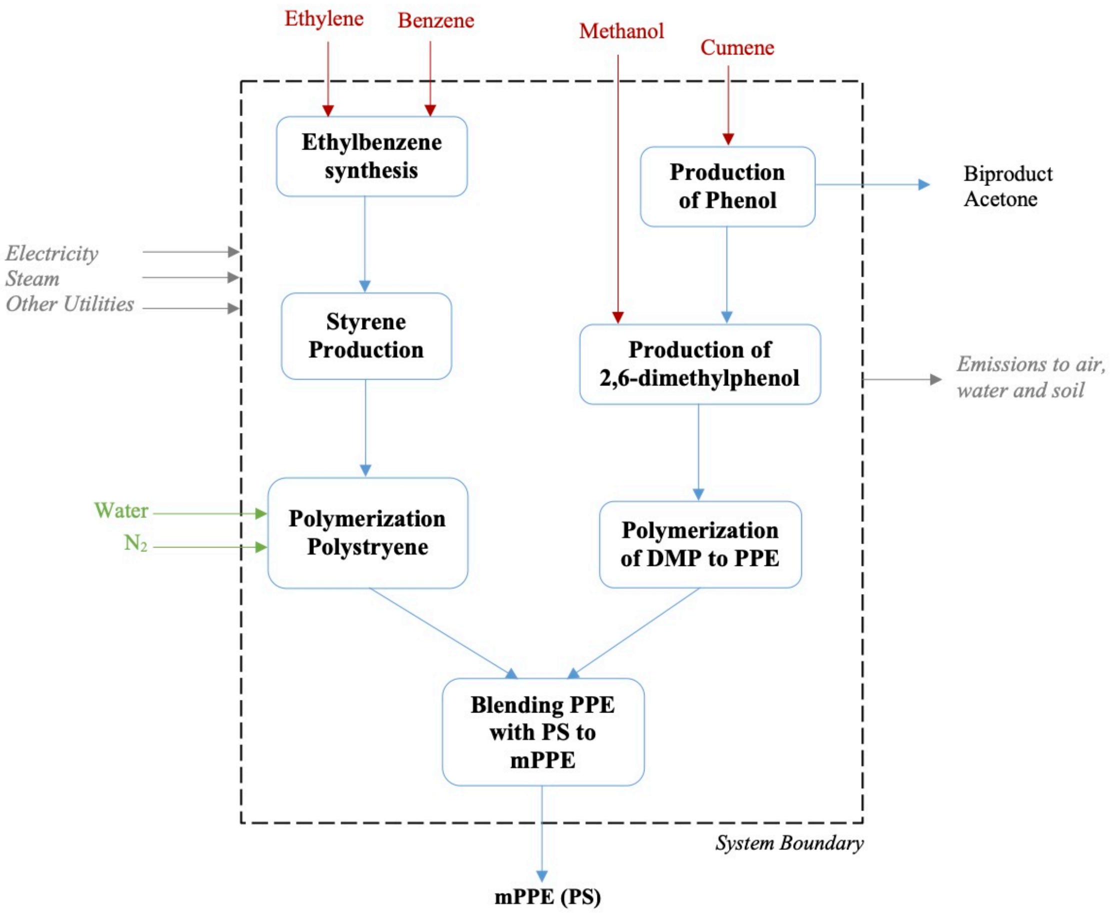

Figure 13: System boundary for the production of mPPE (PS). The red arrows indicate a fossil-based raw material, and the green indicates a non-fossil based raw material. The dotted line shows the system boundary.

The phenol accounted for is produced via the cumene process where cumene is oxidized to form phenol and the coproduct acetone. Phenol and methanol are then reacted with each other together with a catalyst (MgO) to form 2,6-dimethylphenol (DMP). The DMP is then in the third step polymerized, using toluene as the solvent and a copper oxide catalyst, to form PPE.

For the first step in the production of PS benzene is alkylated with ethylene in a gas phase reactor forming ethylbenzene. The ethylbenzene is then dehydrogenated to styrene. The final step is the polymerization of styrene to form polystyrene (PS). The last step included in the system boundary is the blending of PS and PPE forming mPPE (PS), the composition is determined to a 50/50 wt% blend.

ELO product system

The system boundary for ELO production, described in *Figure 14*, contains the extraction of linseed oil that is then used in the synthesis of raw ELO. It also contains the production of maleic anhydride and dipropylene glycol that is used in the synthesis of the crosslinker, a maleic monoester. The final step that is included in the ELO product system is the curing of ELO. In *Figure* 14, the origin of the raw material is also described according to the color combination:

- Green: non-fossil based raw material
- Red: fossil-based raw material

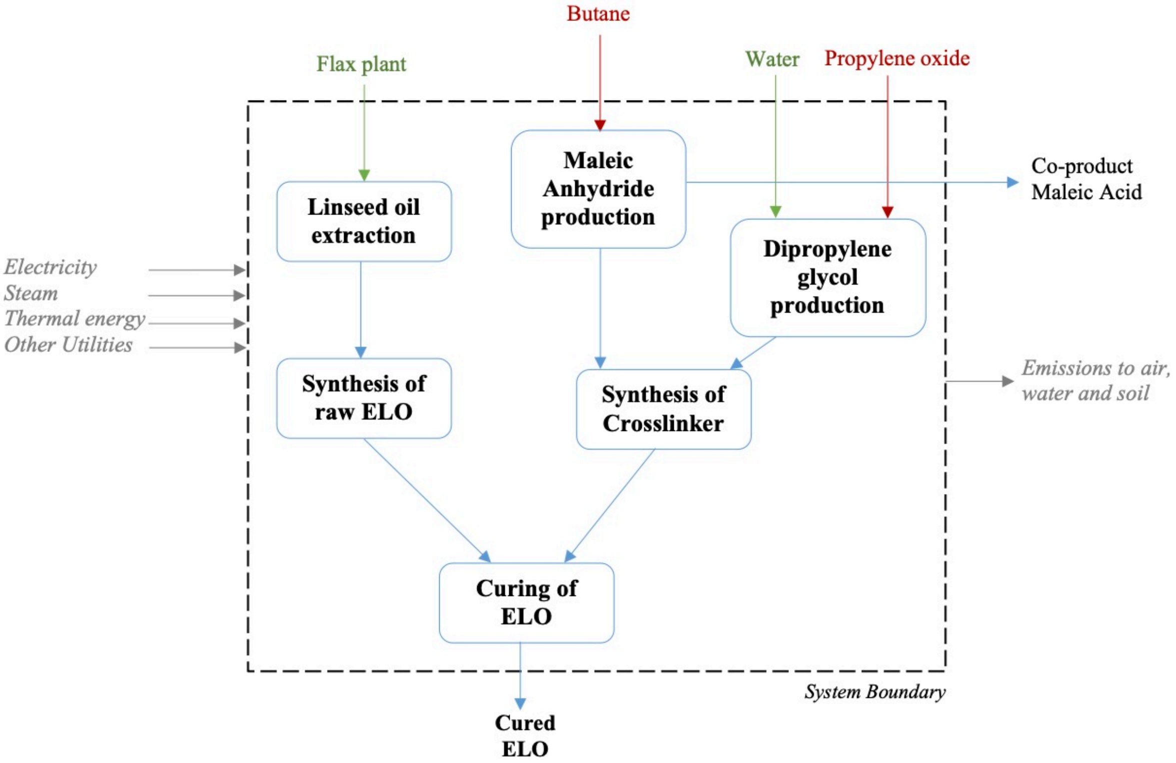

Figure 14: System boundary for the production of ELO. The red arrows indicate a fossil-based raw material, and the green indicates a non-fossil based raw material. The dotted line shows the system boundary.

The flax oil extraction includes the cultivation of the flax plant (sowing, fertilizing, and harvesting of the crops) as well as the transportation of the crop from the field to the oil mill where the oil is produced. The synthesis of the raw ELO includes the chemicals used in the synthesis, electricity, natural gas and thermal energy. These parameters are linearly scaled up from lab scale due to lack of information of production scale processes.[50] The maleic anhydride included in this product system is produced from the so-called butane process in which n-butane is oxidized to form maleic anhydride. The dipropylene glycol used is produced by hydration by propylene oxide in aqueous steam. In the crosslinker synthesis, only the data of raw materials are included of maleic anhydride and dipropylene glycol. At last, the ELO is cured by reacting the crosslinker with the raw ELO, and just as in the crosslinker synthesis step, only the ratio of raw ELO and the crosslinker is accounted for.

EMAA product system

The system boundary for the production of EMAA is described in *Figure* 15. It contains the production of hydrogen cyanide (HCN), the synthesis of acetone cyanohydrin, the production of methacrylic acid and at last the copolymerization of EMAA. The figure also describes the origin of the raw materials according to the color combination:

- Green: non-fossil based raw material
- Red: fossil-based raw material

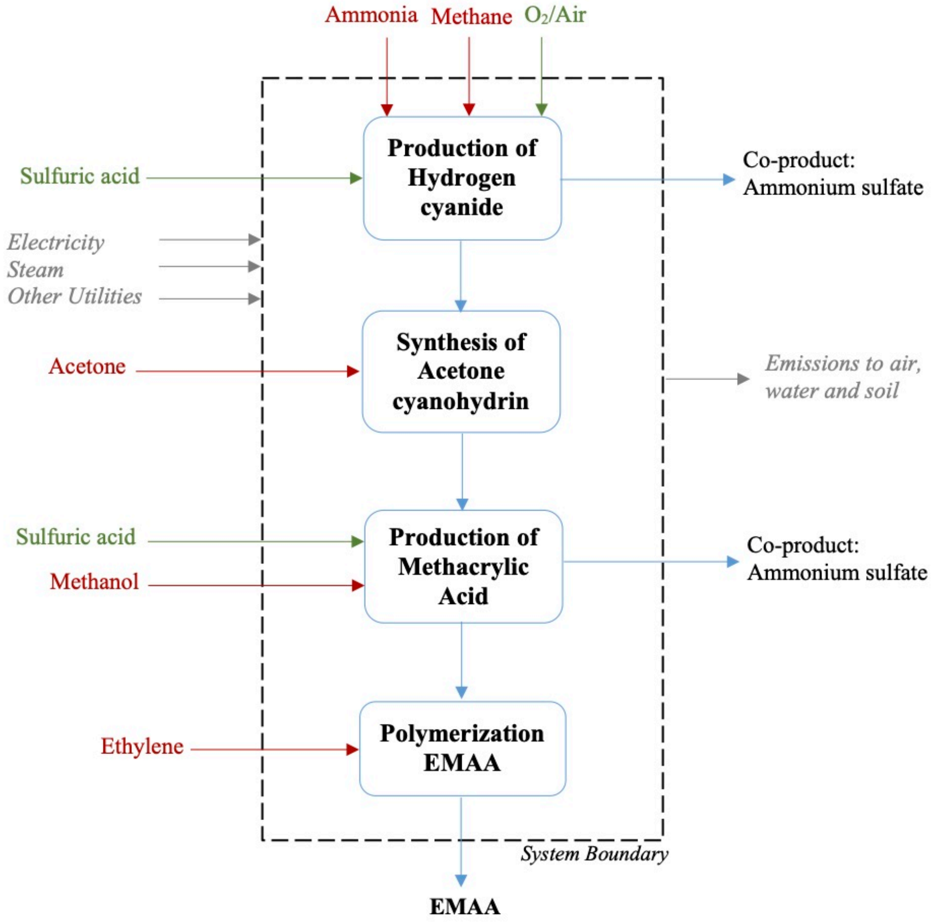

Figure 15: System boundary for the production of EMAA. The red arrows indicate a fossil-based raw material, and the green indicates a non-fossil based raw material. The dotted line shows the system boundary.

The first step in this product system is the production of HCN. HCN is manufactured through the Andrussow process or the Degussa process in which both ammonia and methane are reacted with each other, resulting in the coproduct ammonium sulphate. In the second step, acetone is reacted with HCN to form acetone cyanohydrin. The third step is the production of methacrylic acid (MAA) where sulfuric acid, methanol and acetone cyanohydrin are reacted with each other. Finally, ethylene (produced from steam-cracking of naphtha) and MAA is copolymerized to form EMAA, with the monomer composition is set to 75 wt% ethylene and 15 wt% MAA.

EVA product system

In *Figure* 16 the system boundary of the production of EVA is described. It contains the production of acetic acid, the production of vinyl acetate and lastly the copolymerization of ethylene and vinyl acetate forming EVA. The figure also describes the origin of the raw materials according to the color combination:

- Green: non-fossil based raw material
- Red: fossil-based raw material

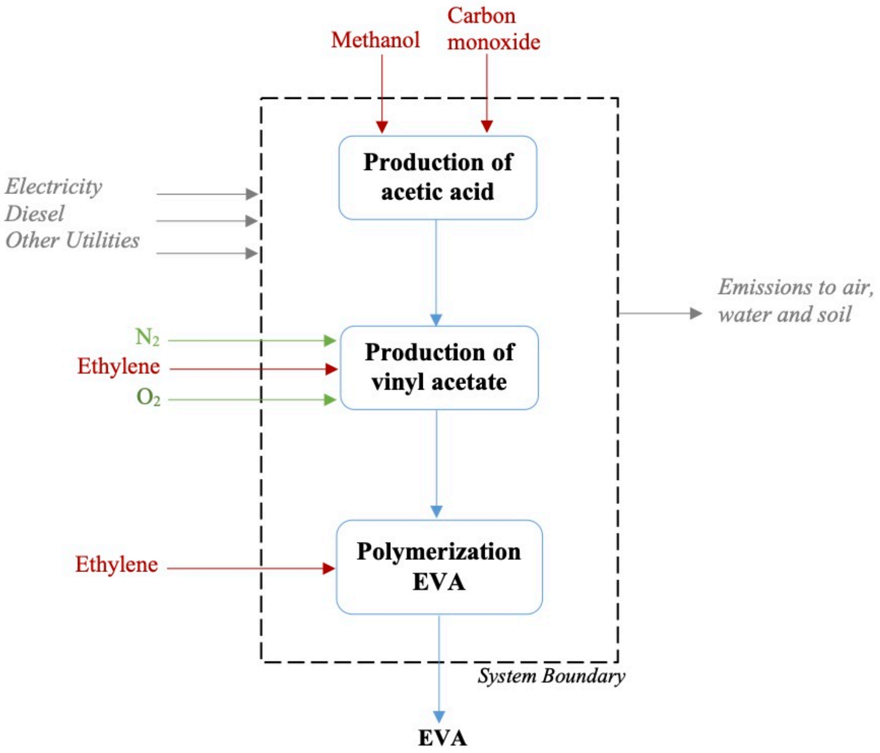

Figure 16: System boundary for the production of EVA. The red arrows indicate a fossil-based raw material, and the green indicates a non-fossil based raw material. The dotted line shows the system boundary.

The methanol used in the production of acetic acid is accounted for as fossil-based. In the production of vinyl acetate, acetic acid is reacted with ethylene in a gaseous phase. The last step included in the product system is the copolymerization of vinyl acetate and ethylene, using the composition 75 wt% ethylene and 15 wt% vinyl acetate. The ethylene accounted for is steam cracked from naphtha.

4.2.2 LCIA Methodology

4.2.2.1 Thinkstep GaBi-Software

The simulations of the environmental impact of the polymers have been set up in the LCA software GaBi Education 9.2.1 developed by Thinkstep. GaBi is an LCA software used for simulating the environmental impacts of processes and plans to evaluate the sustainability of a product or process. GaBi contains a large number of LCA databases providing generic data where specific data is missing. It is also possible to insert specific data into GaBi to combine with generic data from the databases. Different LCIA methods are also provided by GaBi Software, including CML 2001 (baseline), ReCiPe 2016 (midpoint) and TRACI 2.1. This will be further discussed in section *4.2.2.2 LCIA methods*.

4.2.2.2 LCIA methods

A characterization method translates environmental load into impact which is a crucial part of the LCIA. There are different models of how to calculate the environmental impact and therefore different results may be obtained depending on the method used. In this analysis the method of CML 2001 (baseline) is used for the calculations of the results. The impact categories based on this method is described in the next section.

4.2.2.3 Impact categories

The choice of impact categories for this study is based on those categories and LCIA method that Forbo Flooring Systems uses in their LCA's and EPD's for their products (CML 2001). By using the same LCIA method, the results of this study will be comparable with already existing LCA's and future studies of flooring materials that Forbo might conduct. The impact categories chosen can be seen in *Table 1*, together with the unit for each impact category and a description of it.

Table 1: Description and unit specification of the impact categories. [10]

Impact category	Unit	Description
Global warming potential (GWP) (time horizon: 100 years)	kg CO_2 eq	The ratio between increased infrared absorption caused by a substance in relation to the increased infrared absorption caused by 1kg of CO_2.
Acidification Potential (AP)	kg SO_2 eq	The number of H^+ ions formed per kg substance relative to SO_2.
Eutrophication Potential (EP)	kg PO_4^{-3} eq	The increased biological productivity due to emissions of excessive nutrients (nutrification) in relation to phosphate.
Ozone Layer Depletion Potential (ODP)	kg R11 eq	The change in the stratospheric ozone column in the steady-state due to kg emissions of a substance in relation to that of R-11
Photochemical Ozone Creation Potential (POCP)	kg ethylene eq (kg formed ozone/kg)	The formation of ozone in the lower atmosphere due to photo-oxidant emissions relative to ethylene.
Abiotoc Depletion Potential Elements (ADPE)	kg Sb eq	The ratio of the annual production of an abiotic substance (non-renewable resource) divided by the ultimate reserve of this resource in relation to the same ratio of Sb. [51]
Abiotic Depletion Potential Fossil (ADPF)	[MJ]	The ratio between the consumption of natural fossil resources and the ultimate reserve.
Human Toxicity Potential (HTP)	kg 1,4-DCB eq	The emission of human-toxic substances in relation to 1,4-DCB.
Ecotoxicity Potential (ETP)	kg 1,4-DCB eq	The emission of Eco-toxic substances in relation to 1,4-DCB

4.2.3 LCA Data

The data collected for the LCA derives from literature, calculations and the databases in the software GaBi Education 9.2.1. Processes and data for PVC, PS, phenol and acrylic acid were available in the GaBi-Database. For the processes that were not available in GaBi, the data has been taken from literature where it has been found or it has been calculated. In those cases where a certain reactant or chemical has not been available in GaBi, another chemical that is similar has been used instead. As far as possible, generic data covered for Europe has been used since Forbo has no specific supplier of the polymers. In a few cases, sources have been used that are not generic data from Europe but where the judgement has been made that the estimation is acceptable.

4.2.4 Cut-off criteria

The cut-off criteria most used is that the input materials that result in less than 1% of the mass of the final product will be cut-off unless it has a great impact on the analysis. However, the sum of the cut-offs must not exceed 5% of the output. This will also be used in this study.

In the analysis some of the flows have been eliminated based on the cut-off criteria. These can be seen in *Table* 2. The processes which exist in GaBi also follow this criterion and the cut-offs are pre-calculated in GaBi. For the processes that are not available in GaBi, where data from literature and calculations has been used, the cut-offs have been done manually.

Table 2: List of chemicals that have been cut-off and in which process they are used.

Production of mPPE (PS)	
Cuprous oxide	Catalyst in PPE polymerization
Hydrobromic acid	Used in PPE polymerization
Sodium hydroxide	Used in Methanol synthesis
Trisodium phosphate	Used in Methanol synthesis
Water	Reactant in MgO production
Production of EVA	
Pd-catalyst	Catalyst in VAM production
Peroxide initiator	Initiator in EVA polymerization
Production of EMAA	
Initiator	Initiator in EMAA polymerization

4.2.5 Allocations

In the figures for the product systems in section *4.2.1.3 Product systems*, coproducts are formed in some of the process steps. These coproducts need to be accounted for in the analysis since they should also hold a share of the impacts. To do this, allocations have been made where the total impacts have been divided by the products. The allocations made in this study have been accounted for in the Software GaBi according to market value, net calorific value, exegetic content and mass.

4.3 Life Cycle Inventory (LCI)

The data used in the LCA is described in the tables below where it can be seen from what source the data comes from, in what geographical area and for which time period the data is valid for. Some of the chemicals were not available in the database and they have therefore been substituted with another chemical that is similar. *Table 3* describes the data for the PVC production.

Table 3. Overview of the Materials and processes used for PVC and the datasets used in the software GaBi. The geographical coverage and the time related coverage are also stated.

Material/Process & Dataset	Data source	Region	Reference year	Valid until
PVC production				
Poly(vinyl chloride) granulate (suspension; S-PVC) mix	GaBi Software	Europe	2019	2022

In *Table 4* the processes for mPPE (PS) production can be seen. For this process some of the data was not available in the GaBi-database and has therefore been substituted with something similar. Hexamethylenediamine (HMDA; via adipic acid) was used instead of DMBA, DBA and diamine mix for the polymerization of PPE and calcium hydroxide was used instead of magnesium hydroxide in the production of magnesium oxide (the catalyst in DMP production).

Table 4: Overview of the Materials and processes used for mPPE (PS) and the datasets used in the software GaBi. The geographical coverage and the time related coverage are also stated.

Material/Process & Data set	Data source	Region	Reference year	Valid until
mPPE (PS) production	S. Madival, et. al (2009),[52] R.S. Clough, M.A. Perez (2003)[53]	Europe	2009	-
Electricity grid mix	GaBi Software	Europe	2016	2022
Polystyrene granulate (PS) mix	GaBi Software	Germany	2019	2022
PPE polymerization	S. Sreeramagiri, et. al (2020) [54]	-	2020	-
Toluene	GaBi Software	Germany	2019	2022
Hexamethylenediamine (HMDA; via adipic acid)	GaBi Software	Germany	2018	2021
DMP production	F. Cavani, et. al (2009)[55]	-	2009	-
Phenol	GaBi Software	Germany	2019	2022
Nitrogen gaseous	GaBi Software	Germany	2019	2022
Methanol production	Z. Chen, et. al (2019)[56]	China	2019	-
Electricity grid mix	GaBi Software	Europe	2016	2022
Natural gas mix	GaBi Software	Europe	2016	2022
Oxygen (gaseous)	GaBi Software	Germany	2019	2022
Water (desalinated; deionized)	GaBi Software	Germany	2019	2022
Fresh water (Tap water from ground water)	GaBi Software	Europe	2019	2022
Magnesium oxide production	S. Ruan, C. Unluer (2016)[57]	-	2016	-
Calcium hydroxide	GaBi Software	Germany	2019	2022
Hard coal mix	GaBi Software	Germany	2016	2022
Diesel mix at refinery	GaBi Software	Europe	2016	2019

Electricity grid mix	GaBi Software	Europe	2016	2022

The materials and processes used for ELO are depicted in *Table 5*. The process for magnesium sulphate production was not found; instead, the production of magnesium oxide was used (the same process as in mPPE (PS) production). In the crosslinker production, propylene glycol was used instead of dipropylene glycol.

Table 5: Overview of the Materials and processes used for ELO and the datasets used in the software GaBi made by Thinkstep. The geographical coverage and the time related coverage are also stated.

Material/Process/Data set	Data source	Region	Reference year	Valid until
ELO	Y. Deng et. al (2016)[50] & calculations	Europe	2016	-
Linseed oil extraction				
Rapeseed oil production	J. Schmidt (2010)[58]	Denmark	2010	-
Raw ELO synthesis	Y. Deng et. al (2016)[50] & calculations	Europe	2016	-
Acetic acid from Methanol (low pressure carbonylation)	GaBi Software	Germany	2019	2022
Electricity grid mix	GaBi Software	Europe	2016	2022
Hydrogen peroxide	GaBi Software	Germany	2019	2022
Sodium hydroxide (from chlorin-alkali electrolysis, diaphragm)	GaBi Software	Germany	2019	2022
Process steam from natural gas 85%	GaBi Software	Europe	2016	2022
Thermal energy from natural gas	GaBi Software	Europe	2016	2022
Magnesium oxide production	S. Ruan, C. Unluer (2016)[57]	-	2016	-
Calcium hydroxide	GaBi Software	Germany	2019	2022
Process water	GaBi Software	Europe	2019	2022
Hard coal mix	GaBi Software	Germany	2016	2022
Diesel mix at refinery	GaBi Software	Europe	2016	2019
Electricity grid mix	GaBi Software	Europe	2016	2022
Crosslinker production	D. T. Carter (2008)[42] & calculations	-	2008	-
Propylene glycol	GaBi Software	Germany	2019	2022
Maleic Anydride production (Butane technology)	P. Vaz Mangili, et. al (2018)[43]	-	2018	-
Process-water	GaBi Software	Europe	2019	2022
Thermal energy from natural gas	GaBi Software	Europe	2016	2022
Curing of ELO	D. T. Carter (2008)[42] & calculations	-	2008	-

In *Table 6* an overview of the data used in EMAA production is shown. LCA data was not found for methacrylic acid production and was therefore replaced by data for methyl methacrylate.

Table 6: Overview of the Materials and processes used for EMAA and the datasets used in the software GaBi. The geographical coverage and the time related coverage are also stated.

Material/Process/Data set	Data source	Region	Reference year	Valid until
EMAA				
Polymerization of EMAA	C. Liptow, A. Tillman (2008)[59], G. Wypych (2012)[60]	-	2008, 2012	-
Ethylene	GaBi Software	Germany	2019	2022
Electricity grid mix	GaBi Software	Europe	2016	2022
Diesel mix at refinery	GaBi Software	Europe	2016	2019
Production of Methacrylic acid				
Methyl methacrylate	European Plastics, MMA (2014)[61]	Europe	2014	-

The data for EVA production is seen in *Table 7*. No substitutions have been made since all materials were found in GaBi-Database.

Table 7: Overview of the Materials and processes used for EVA and the datasets used in the software GaBi. The geographical coverage and the time related coverage are also stated.

Material/Process/Data set	Data source	Region	Reference year	Valid until
EVA				
Polymerization of EVA	C. Liptow, A. Tillman (2008)[59], G. Wypych (2012)[60]	-	2008, 2012	-
Ethylene	GaBi Software	Germany	2019	2022
Diesel mix at refinery	GaBi Software	Europe	2016	2019
Electricity grid mix	GaBi Software	Europe	2016	2022
Vinyl Acetate production	R. Renneke, et. al (2006)[48]	-	2006	-
Acetic acid from Methanol (low pressure carbonylation)	GaBi Software	Germany	2019	2022
Ethylene	GaBi Software	Germany	2019	2022
Oxygen (gaseous)	GaBi Software	Germany	2019	2022
Nitrogen (gaseous)	GaBi Software	Europe	2019	2022

4.4 Life Cycle Impact Assessment (LCIA)

From the life cycle impact assessment, results for each polymer have been obtained for each impact category. These are depicted in *Table 8*.

Table 8: LCIA results for the studied polymers for each impact category.

Impact category	Unit	S-PVC	mPPE (PS)	ELO	EMAA	EVA
Global Warming Potential (GWP 100 years)	kg CO_2 eq	2.13	6.03	3.85	2.93	2.97
Ozone Layer Depletion Potential (ODP. Steady state)	kg R11 eq	1.86×10^{-10}	7.39×10^{-14}	8.83×10^{-8}	4.86×10^{-8}	4.73×10^{-14}
Acidification Potential (AP)	kg SO_2 eq	0.00289	0.00986	0.0125	0.00718	0.005
Eutrophication Potential (EP)	kg PO_4^{-3} eq	4.75×10^{-4}	0.00119	75.8	7.86×10^{-4}	5.78×10^{-4}
Photochemical Ozone Creation Potential (POCP)	kg Ethylene eq	7.24×10^{-4}	0.00136	6.92×10^{-4}	5.97×10^{-4}	5.44×10^{-4}
Abiotic Depletion Potential Elements (ADPE)	kg Sb eq	8.72×10^{-6}	1.61×10^{-6}	2.74×10^{-6}	7.13×10^{-7}	8.38×10^{-7}
Abiotic Depletion Potential Fossil (ADPF)	[MJ]	49.9	212	29.3	63	85.9
Human toxicity Potential (HTP)	kg 1,4-DCB eq	0.0787	0.301	0.0399	0.116	0.139
Freshwater Aquatic Ecotoxicity Potential (FAETP)	kg 1,4-DCB eq	0.0117	0.0565	0.00453	0.018	0.0239
Marine Aquatic Ecotoxicity Potential (MAETP)	kg 1,4-DCB eq	113	429	53.5	225	248
Terrestric Ecotoxicity Potential (TETP)	kg 1,4-DCB eq	0.00419	0.017	0.00439	0.00542	0.00718

The diagram in *Figure 17* illustrates the results for PVC, mPPE (PS), ELO, EMAA and EVA based on the chosen impact categories. The results for each polymer are related to the polymer with the highest impact in the specific impact category.

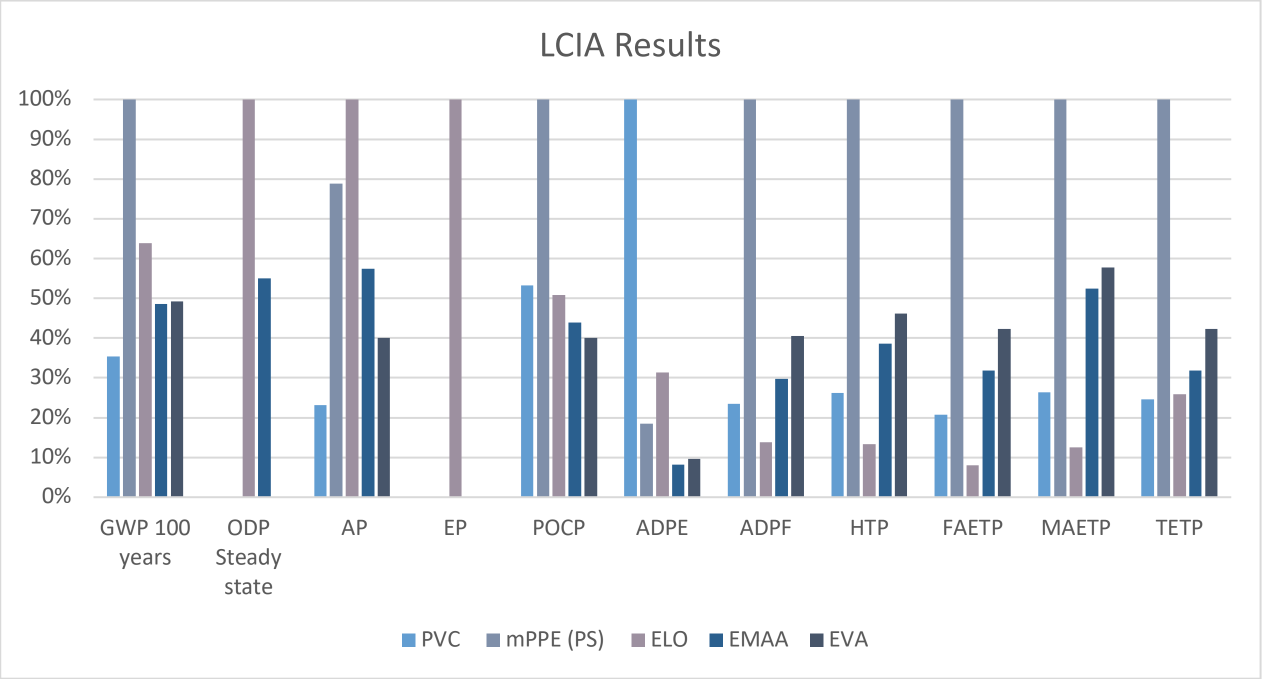

Figure 17: LCIA results from the life cycle assessment of the production of the polymers PVC, mPPE (PS), ELO, EMAA and EVA. The results have been converted to percentages of the impact from the polymer with highest impact in each category.

What can be seen in the table and diagram is that mPPE (PS) has the highest impact for global warming potential (GWP), photochemical ozone creation potential (POCP), abiotic depletion of fossils (ADPF), human toxicity potential (HTP) and the three ecotoxicity potentials (ETP): freshwater aquatic (FAETP), marine aquatic (MAETP) and terrestric (TETP) ETP. In these categories the polymer with the second highest impact has a value of 64% or less. For ozone layer depletion potential (ODP), acidification potential (AP) and eutrophication potential (EP) ELO has the highest impact. It is especially high for the eutrophication potential (EP) where the polymer with the second highest impact has a value of 0.0016% of that of ELO. PVC has the highest impact on abiotic depletion of elements, the second highest impact is from ELO with a value of 31%.

4.5 Interpretation

4.5.1 Completeness & Consistency check

One part of testing the robustness of the results is to perform a completeness and consistency check. In the completeness test the data gaps in the inventory and/or the impact assessment is documented. For the consistency check the appropriateness of the life cycle modelling given the defined goal and scope is tested and commented on.

In the following sections the completeness and consistency checks of the materials and processes for the different polymer productions are documented in *Table 9-13.* The completeness check has been categorized as:

- complete (*)
- incomplete (x)

If categorized as complete, no steps in the process or materials are missing. If categorized as incomplete one or more steps in the process are missing.

In the consistency check, following parameters has been included:

- estimations (est.)
- Approximations (approx.)
- Calculations (calc.)
- Deviation from temporal boundary (time)
- Deviation from geographical boundary (geography)

Inconsistency is documented if a process or parameter is estimated, approximated or calculated. Also, if there is a deviation from the temporal or geographical boundary of the source, this is also documented. Processes that are incomplete or inconsistent are also commented in the tables for further explanation.

S-PVC

The data used in the LCA for S-PVC was found as a complete process in the GaBi-Database and is therefore complete with all the steps in the process included.

Table 9: Completeness & consistency check for the material and processes used in the LCA of S-PVC. The completeness check is categorized as complete (*) or incomplete (x). The consistency check includes the parameters: estimation (est.), approximation (approx.), deviation from temporal boundary (time), deviation from geographical boundary (geograph.) and calculations (calc.). The completeness and consistency of a process is also commented.

Material/Process & Dataset	Completeness	Consistency	Comment
Poly(vinyl chloride) granulate (suspension; S-PVC) mix (EU-28)	*		

mPPE(PS)

The mPPE (PS) production process was probably the hardest to find information about and has therefore a few processes that are incomplete or inconsistent. For the mPPE (PS) production step, the energy consumption of extrusion of another polymer (PLA) was used and the ratios of PPE and PS was chosen to 50/50 based on source (see *Table 4*). No spill of the extrusion process was accounted for, meaning a 100% yield, since no data on this was found.

In the PPE polymerization step the energy consumption is not accounted for. When looking at the LCIA results of e.g., PVC where energy consumption is included, the energy in the production steps is not a major contributor to the environmental load. Since mPPE (PS) is polymerized under mild conditions (room temperature and 1atm), it is therefore assumed that the incompleteness will not affect the results greatly. Since no data on the yield was found, no spill was accounted for, just as in the mPPE (PS) production step.

For the production step of DMP the ratios of the chemicals used has been calculated based on reference with the yield of 80%. Just as for the PPE polymerization step, the energy consumption is not accounted for. This is perhaps one of the inconsistencies that will affect the results the most since the reaction is executed in elevated temperatures (350-380°C) in gaseous phase. Moreover, the reaction is exothermic which probably would require cooling as well as initial heating. Due to this rather complicated system, and since no comparable results has been found, no estimated energy consumption has been included in this system. Furthermore, gaseous nitrogen is used as the inert gas in the reaction and can most likely be reused and recirculated in a production scale system, this has neither been accounted for.

The source used for the methanol production has the geographical coverage of China. This process is assumed to have a similar impact as if it had been produced in Europe since the transport is not included and the raw materials accounted for in GaBi has the geographical boundary for Europe. Lastly, the magnesium hydroxide has been approximated to calcium hydroxide which is assumed to be a very good approximation.

Table 10: Completeness & consistency check for the material and processes used in the LCA of mPPE (PS). The completeness check is categorized as complete (*) or incomplete (x). The consistency check includes the parameters: estimation (est.), approximation (approx.), deviation from temporal boundary (time), deviation from geographical boundary (geography) and calculations (calc.). The completeness and consistency of a process is also commented on.

Material/Process & Data set	Completeness	Consistency	Comment
mPPE (PS) production	*	approx., calc.	Energy consumption approximated & calculated from extrusion of PLA based on source. No spill is accounted for.
Electricity grid mix (EU-28)	*		
Polystyrene granulate (PS) mix (DE)	*		
PPE polymerization	x	approx.	Accounted for 100% yield. The energy consumption is not accounted for.
Toluene (DE)	*		
Hexamethylenediamine (HMDA; via adipic acid) (DE)	*	approx.	Approximation for a mixture of DMBA, DBA & Diamine mix
DMP production	x	calc./est., approx..	The chemicals used has been calculated using 80% yield based on reference. The energy consumption is not accounted for and the N_2 is not recirculated in the system.
Phenol (DE)	*		
Nitrogen gaseous (DE)	*		
Methanol production	*	geography	China
Electricity grid mix (EU-28)	*		
Natural gas mix (EU-28)	*		
Oxygen (gaseous) (DE)	*		
Water (desalinated; deionized) (DE)	*		

Fresh water (Tap water from ground water) (EU-28)	*		
Magnesium oxide production			
Calcium hydroxide (DE)	*	approx.	Calcium hydroxide approximated to magnesium hydroxide.
Hard coal mix (DE)	*		
Diesel mix at refinery (EU-28)	*		
Electricity grid mix (EU-28)	*		

ELO

The first inconsistency for the production of ELO is the linseed oil that is approximated to the impact of rapeseed oil. This is assumed to be a good estimation because of the similar growing conditions needed and the high oil content of the seeds. Magnesium oxide and magnesium hydroxide are approximated with magnesium sulphate and calcium hydroxide respectively. Both approximations are assumed to be good due to the similar production processes of the chemicals.

In the production of crosslinkers the energy consumption is not accounted for. The ratios of the chemicals used were calculated based on source with the yield assumed to be 100%. As mentioned for the PPE polymerization step, it is assumed that the impact from the raw materials is much greater than for the energy consumption and therefore the missing data do not affect the results greatly. The source also deviates from the temporal boundary. However, the cured ELO using the maleic monoester mentioned in study by D.T Carter et.al is not a commercial product and the method for producing it is on a laboratory scale. Therefore, it has no effect on the results that the source is outside the temporal boundary. This is also the case for the curing of ELO.

The dipropylene glycol production is assumed to have the same environmental impact since the production process is essentially the same for both chemicals. For the maleic anhydride production not all impact categories are accounted for in the LCI due to lack of information.

Table 11: Completeness & consistency check for the material and processes used in the LCA of ELO. The completeness check is categorized as complete (*) or incomplete (x). The consistency check includes the parameters: estimation (est.), approximation (approx.), deviation from temporal boundary (time), deviation from geographical boundary (geography) and calculations (calc.). The completeness and consistency of a process is also commented on.

Material/Process/Data set	Completeness	Consistency	Comment
Raw ELO synthesis	*		
Rapeseed oil extraction (DK)	*	approx.	Linseed oil approximated to rapeseed oil.
Acetic acid from Methanol (low pressure carbonylation) (DE)	*		
Electricity grid mix (EU-28)	*		

Hydrogen peroxide (DE)	*		
Sodium hydroxide (from chlorin-alkali electrolysis, diaphragm) (DE)	*		
Process steam from natural gas 85% (EU-28)	*		
Thermal energy from natural gas (EU-28)	*		
Magnesium oxide production	*	approx.	Magnesium sulphate approximated to magnesium oxide.
Calcium hydroxide (DE)	*	approx.	Magnesium hydroxide approximated to calcium hydroxide.
Process water (EU-28)	*		
Hard coal mix (DE)	*		
Diesel mix at refinery (EU-28)	*		
Electricity grid mix (EU-28)	*		
Crosslinker production	x	est., calc., time	The energy consumption is not accounted for. Accounted for 100% yield and calculated ratios based on source. Source from 2008.
Propylene glycol (DE)	*	approx.	Dipropylene glycol approximated to propylene glycol.
Maleic Anydride production (Butane technology)	x		Not all impact categories are accounted for.
Process-water (EU-28)	*		
Thermal energy from natural gas (EU-28)	*		
Curing of ELO	x	est., calc., time	The energy consumption is not accounted for. Accounted for 100% yield and calculated ratios based on source. Source from 2008.

EMAA

The approximations made for the production of EMAA are few. First is the approximation made for the energy consumption of the polymerization step of EMAA. Due to a similar polymerization method as for LDPE, this is the energy used. The second approximation is that no spill is accounted for in the polymerization step. Lastly, the impact of methacrylic acid is approximated to that of methyl methacrylate, which has similar production processes, and is therefore assumed to be a good approximation. The composition of the copolymer was chosen to be an average of the compositions used for EMAA.

Table 12: Completeness & consistency check for the material and processes used in the LCA of EMAA. The completeness check is categorized as complete (*) or incomplete (x). The consistency check includes the parameters: estimation (est.), approximation (approx.), deviation from temporal boundary (time), deviation from geographical boundary (geography) and calculations (calc.). The completeness and consistency of a process is also commented on.

Material/Process/Data set	Completeness	Consistency	Comment
Polymerization of EMAA	x	approx.	The energy required is approximated to that of polymerization of LDPE. No spill accounted for.
Ethylene (DE)	*		
Electricity grid mix (EU-28)	*		
Diesel mix at refinery (EU-28)	*		
Methyl methacrylate production	*	approx.	Methacrylic acid approximated to methyl methacrylate.

EVA

The polymerization process of EVA is approximated to that of LDPE, as explained in the section above, due to the similar method of polymerization. This is assumed to be a good approximation. No spill is accounted for, meaning 100% yield of the polymerization.

The ratios of the chemicals used in the vinyl acetate production is calculated based on information in source. Though the source is outside the temporal boundary, the same process is still used today.[47] The energy consumption is neither accounted for in the vinyl acetate production. The composition was chosen to be an average of the compositions used for EVA.

Table 13: Completeness & consistency check for the material and processes used in the LCA of EVA. The completeness check is categorized as complete (*) or incomplete (x). The consistency check includes the parameters: estimation (est.), approximation (approx.), deviation from temporal boundary (time), deviation from geographical boundary (geography) and calculations (calc.). The completeness and consistency of a process is also commented on.

Material/Process/Data set	Completeness	Consistency	Comment
Polymerization of EVA	x	approx.	The energy required is approximated to that of polymerization of LDPE. No spill accounted for.
Ethylene (DE)	*		
Electricity grid mix (EU-28)	*		
Diesel mix at refinery (EU-28)	*		
Vinyl Acetate production	x	est., calc., time	The energy consumption is not accounted for.

			The ratios of chemicals calculated based on source. Source from 2006.
Acetic acid from Methanol (low pressure carbonylation) (DE)	*		
Ethylene (DE)	*		
Oxygen (gaseous) (DE)	*		
Nitrogen (gaseous) (EU-28)	*		

4.5.2 Identification of hotspots

In this section hot-spots of the impact categories for each of the polymers will be discussed based on the LCIA results (*Figure* 17). To determine the hotspots a dominance analysis have been performed on the production steps for each polymer (see *Appendix A* – D). These hotspots will be further explored in a sensitivity analysis, section

4.5.3 Sensitivity analysis.

4.5.2.1 PVC

According to the LCIA results, see *Figure* 17, it is disclosed that PVC does not have either higher impact on global warming or acidification than the comparative polymers. However, the abiotic depletion potential for elements (ADPE) is significantly higher for PVC. This is almost exclusively due to the chlorine production according to data taken from a dominance analysis of S-PVC production constructed by Plastics Europe (2015), where it is declared that the chlorine production stands for 97,2% of the ADPE for S-PVC. The chlorine production also stands for 44,2% of the AP, 30,4% of the ODP and 28,9% of the GWP. [62]

The production of ethylene and vinyl chloride monomers (VCM) has also a great effect on the environmental impacts of PVC. Ethylene production stands for 57,5% of the GWP, 34,8% of the ADPF, 33% of the AP, 55,4% of the EP and 51,3% of the POCP. The production of VCM stands for 21,7% of the GWP, 49,6% of the ODP and 28,8% of the POCP. [62] In conclusion, there are three hotspots in the production line of PVC: the chlorine production, ethylene production and the chloride monomer (VMC) synthesis.

4.5.2.2 mPPE (PS)

From the LCIA-results in *Figure* 17 it can clearly be seen that mPPE (PS) has a high impact on the environment. It has the highest climate impact in 7 out of the 11 categories and it is especially high for abiotic depletion potential of fossils (ADPF), human toxicity potential (HTP) and the different ecotoxicity potentials (ETP) where the other polymers have a value of 51% compared to mPPE (PS) or less. It is also very high compared to the others for the global warming potential (GWP) where ELO with the second highest value has a value of 60% compared to mPPE (PS).

In the mPPE (PS) production the blending has been set to 50 wt% of both PPE and PS. From the dominance analysis it is seen that PPE has a contribution of more than 50% in all impact categories except for abiotic depletion potential of elements (ADPE). In the PPE production the DMP production has the highest impact followed by toluene. However, it is worth noting that toluene is used as a solvent, and it might be possible to reuse it. This has not been accounted for in the analysis. The DMP production has a very high ozone layer depletion potential (ODP) which stands for almost all ODP in the PPE production. The hotspots in mPPE (PS) production are the PPE production, in which DMP production has the highest impact.

4.5.2.3 ELO

When comparing the climate impacts of ELO production with the other polymers, it is clear from the LCIA results that ELO has a significantly higher eutrophication potential (EP) and ozone layer depletion potential (ODP). For these two, the linseed oil production is the only contributor (100%) according to the dominance analysis constructed for ELO, see *Appendix A* – D. ELO production has also a large impact on both the acidification potential (AP) and the photochemical ozone creation potential (POCP) in which the linseed oil production is the main contributor with 87,2% and 69,4% respectively.

The production of ELO has a GWP-value of nearly double that of PVC. The crosslinker production stands for 45,7% of this high value and the linseed oil production for 38,4%. Another impact category in which the ELO production scores a high value is ADPE in which the crosslinker stands for 87,2% of the impact.

The two hotspots for the production line of ELO are evidently the crosslinker production and the linseed oil production process. Further investigation of the dominance analysis of the crosslinker production shows that the dipropylene glycol has the largest impact of the crosslinker. On the total impact does propylene glycol stand for 19,2% of the GWP, 85% of the ADPE, 50% of the ADPF, 62,2% of the FAETP, 51,7% of the MAETP and 35,9% of the TETP. The hotspots for ELO are the crosslinker, the propylene glycol production in particular, and the linseed oil production.

4.5.2.4 EMAA

The production of EMAA does not stand out with higher impact in any of the categories compared to the other polymers. However, ODP is significantly higher than PVC where MAA is the only contributor. The acidification potential (AP) is more than double than for PVC. EMAA also has higher ADPF, FAETP and TETP than PVC. According to the dominance analysis the electricity and ethylene production are contributing the most. MAA is the only contributor to ODP and has quite high AP, otherwise it does not contribute significantly to the total impact. The hotspots of the EMAA production are the electricity consumption and ethylene production step.

4.5.2.5 EVA

From the results it can be seen that EVA does not have the highest impact in any category. It has the second highest impact, after mPPE (PS), in abiotic depletion potential of fossils (ADPF), human toxicity potential (HTP) and the ecotoxicity potentials (ETP). The results are fairly similar to those of EMAA, but higher than PVC and ELO. From the dominance analysis it is seen that in the EVA production the ethylene production and electricity are the greatest contributors. Just as in the EMAA production, is the hotspots for EVA the electricity and ethylene production.

4.5.3 Sensitivity analysis

Depending on the result from the dominance analysis, where the hotspots were identified, sensitivity analyses have been performed for the polymers. This has been done by exchanging e.g., raw materials or the supply source of electricity for some of the hotspots in the flows, in the hopes of improving the environmental performance for each of the polymers. Tables for the sensitivity analysis can be seen in *Appendix B* – S.

4.5.3.1 PVC

For PVC, the fossil-based ethylene was substituted with bio-based ethylene. Data from PlasticsEurope was used[62], and it could be seen that the biggest differences happened for GWP, AP and EP. The global warming potential (GWP) decreased by 55%. The acidification potential (AP) and eutrophication potential (EP) were greatly increased with 215% and 1077% respectively. In *Figure* 18 a comparison with the other polymers has been made, where it is visible that the GWP is even lower. However, there were not values for all impact categories, which is why all impact categories are not shown in the figure.

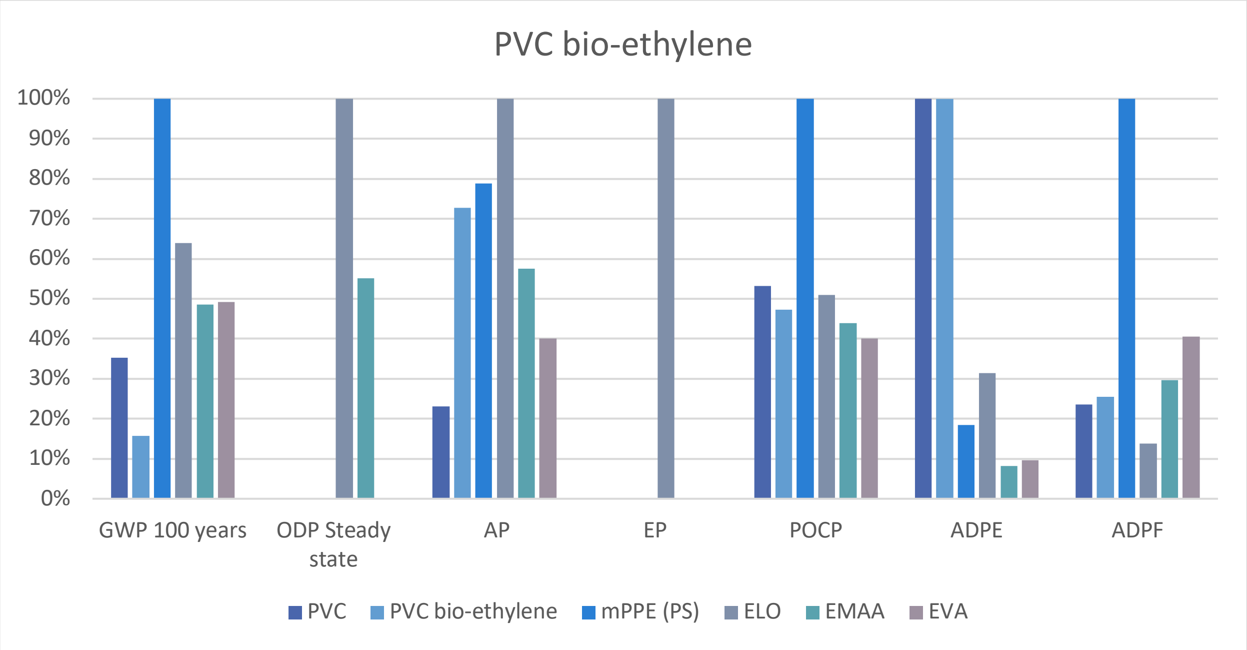

Figure 18: Comparison of the environmental impacts of PVC and bio-PVC with the other polymers. The results have been converted to percentages of the impact from the polymer with highest impact in each category.

4.5.3.2 mPPE (PS)

When methanol is substituted with bio-based methanol the impacts in all categories are decreased except the eutrophication potential (EP) that increases with 1.7%. The global warming potential (GWP) is the impact category where the substitution has had the most effect, it decreased by 75%. The impacts in the other categories have not been reduced as much. When comparing the results to the mPPE (PS), the impacts are about the same except for the global warming potential (GWP), see *Figure* 19. The GWP is the lowest of all polymers when using 100% bio-based methanol.

Since no experiments have been able to be performed the optimum ratios of PPE/PS in a flooring blend is yet unknown, and it is therefore hard to declare the environmental impact of mPPE (PS). In the sensitivity analysis the proportions in the blend have been altered to 40/60, 30/70 and 10/90 of PPE/PS. It was clearly seen that the less PPE and more PS in the blend gave a more environmentally friendly product, see *Figure 19.*The impacts are decreased in all impact categories when less PPE is used. With a composition of 10 wt% PPE and 90 wt% PS the impacts are between 35 and 51% lower compared to a 50/50 wt% blend. Even if the impacts have been significantly lowered, it is still the highest in some of the categories compared to the other polymers. However, mPPE (PS) with lower PPE content are more comparable to the other polymers and do not stand out as much.

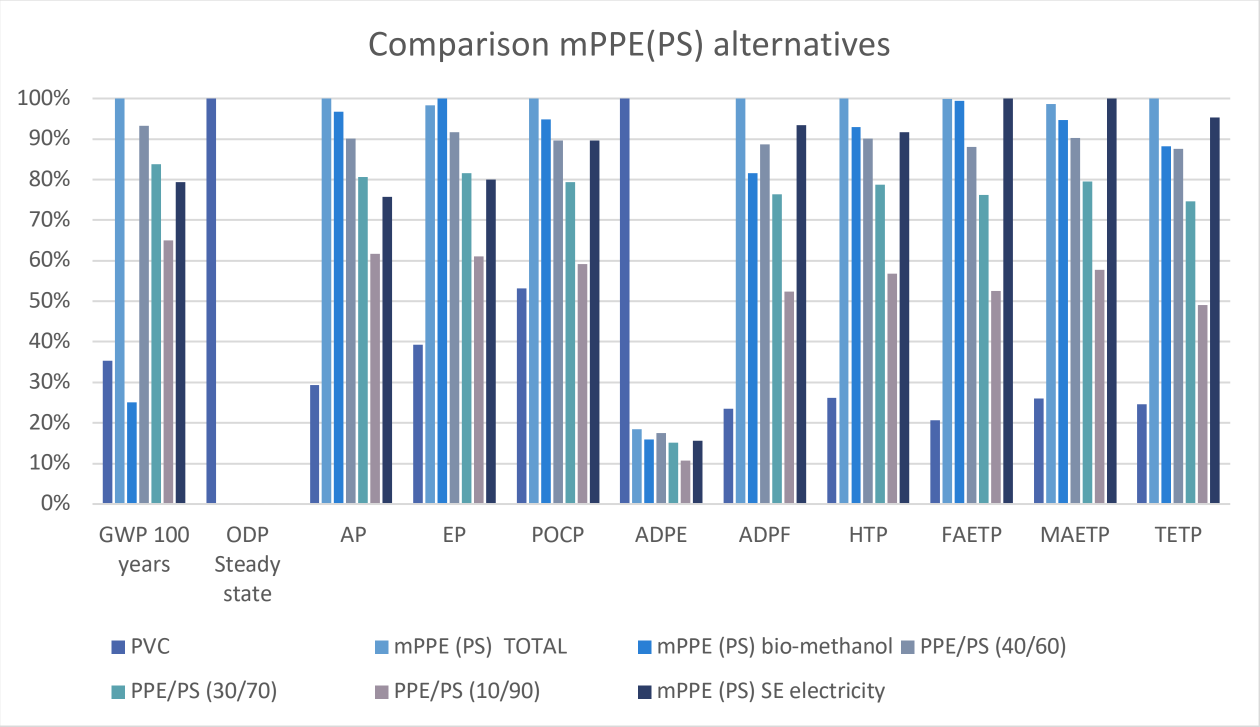

Figure 19: Comparison of the environmental impacts of mPPE (PS) with the other mPPE (PS) alternatives and PVC. The results have been converted to percentages of the impact from the polymer with highest impact in each category.

The electricity was replaced with electricity from Sweden and from Germany. Most of the impacts were reduced when using Swedish electricity, and the ones that were increased did not increase more than 2%. The ozone layer depletion potential (ODP) was the impact category with the biggest change, it decreased by 49%. The global warming potential (GWP) decreased by 21%.

4.5.3.3 ELO

The crosslinker in the ELO production was changed to a partially bio-based crosslinker. This substitution led to an 11% decrease in global warming potential (GWP) and about 50% decrease for abiotic depletion potential of fossils (ADPF) and marine aquatic ecotoxicity potential (MAETP). Terrestric ecotoxicity potential (TETP) was also lowered by 25%. However, the abiotic depletion potential of elements (ADPE), human toxicity potential (HTP) and freshwater aquatic ecotoxicity potential (FAETP) were significantly increased, with 7056%, 240% and 1208% respectively. The ozone layer depletion potential (ODP) increased as well, with 34%. When comparing the ELO with the bio-based crosslinker to PVC and ELO, see *Figure 20,* it can be seen that the ODP is even higher than for the starting point of ELO. It is also seen that ADPE is much higher, PVC is 96% lower.

When substituting the electricity from average European with Swedish electricity the impacts were relatively constant. The impacts did not change more than 3.3%. The electricity was also substituted to energy from biomass. The impact for global warming potential (GWP) and abiotic depletion potential of fossils (ADPF) decreased with 9.1% and 21%. The other impact categories were increased, most with less than 20%. However, human toxicity potential (HTP) increased with 82% and the marine aquatic ecotoxicity potential (MAETP) increased with 885%. In the comparison with the different polymers, it is seen that MAETP is higher than for the other polymers. However, HTP is still lower than for the other polymers even with an increase of 82%.

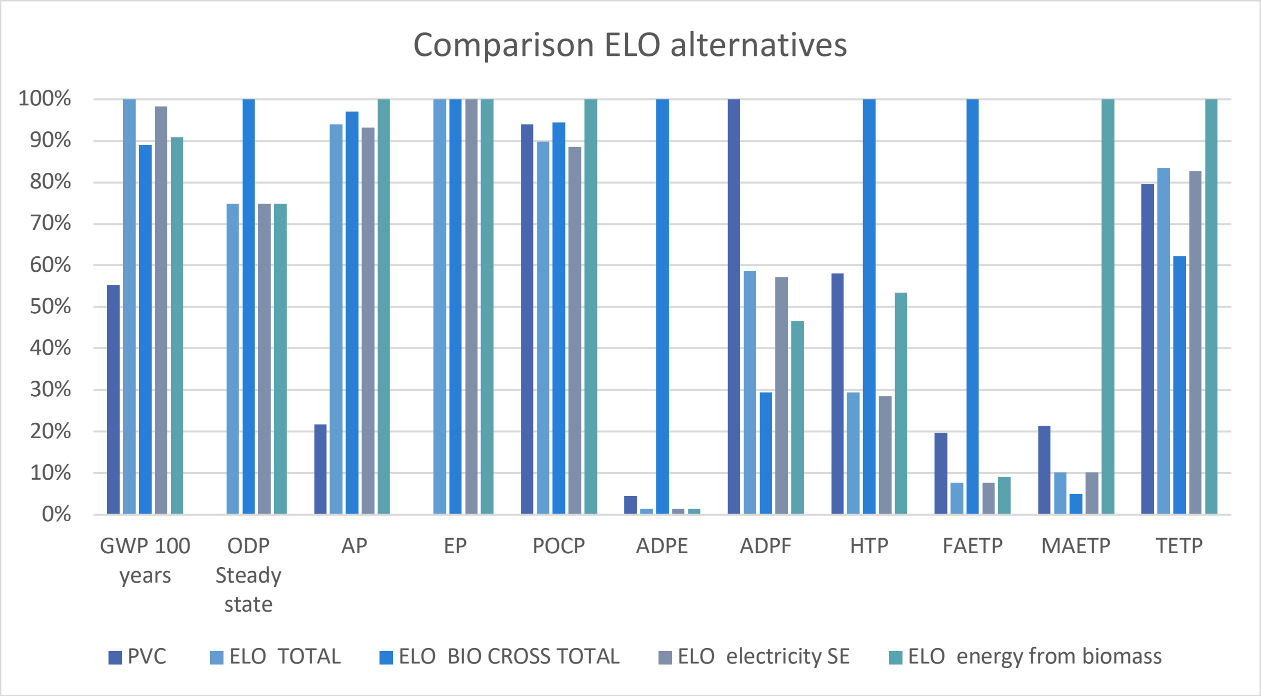

Figure 20: Comparison of the environmental impacts of ELO with the other ELO alternatives and PVC. The results have been converted to percentages of the impact from the polymer with highest impact in each category.

4.5.3.4 EMAA

Fossil-based ethylene was replaced with bio-based ethylene for the copolymerization of EMAA. This gave a 40% decrease in the global warming potential (GWP) and a 6.7% decrease in abiotic depletion potential of fossils (ADPF). For the other categories the impacts were increased. There were three impacts that stood out; eutrophication potential (EP) increased with 506%, abiotic depletion potential of elements (ADPE) increased with 1123%, and freshwater aquatic ecotoxicity potential (FAETP) increased with 117%. In the comparison, it is seen that the EP and AP has increased, however it is still lower than for ELO. The ADPE is as high for EMAA as for PVC, which is significantly higher than for the other polymers. This can be seen in *Figure* 21.

The generic European electricity mix was changed to Swedish, resulting in a reduction of the global warming potential (GWP) with 41%, the acidification potential (AP) and abiotic depletion of elements (ADPE) were decreased with about 25% each. When comparing with PVC it is seen that the biggest change was for GWP which is lower than PVC.

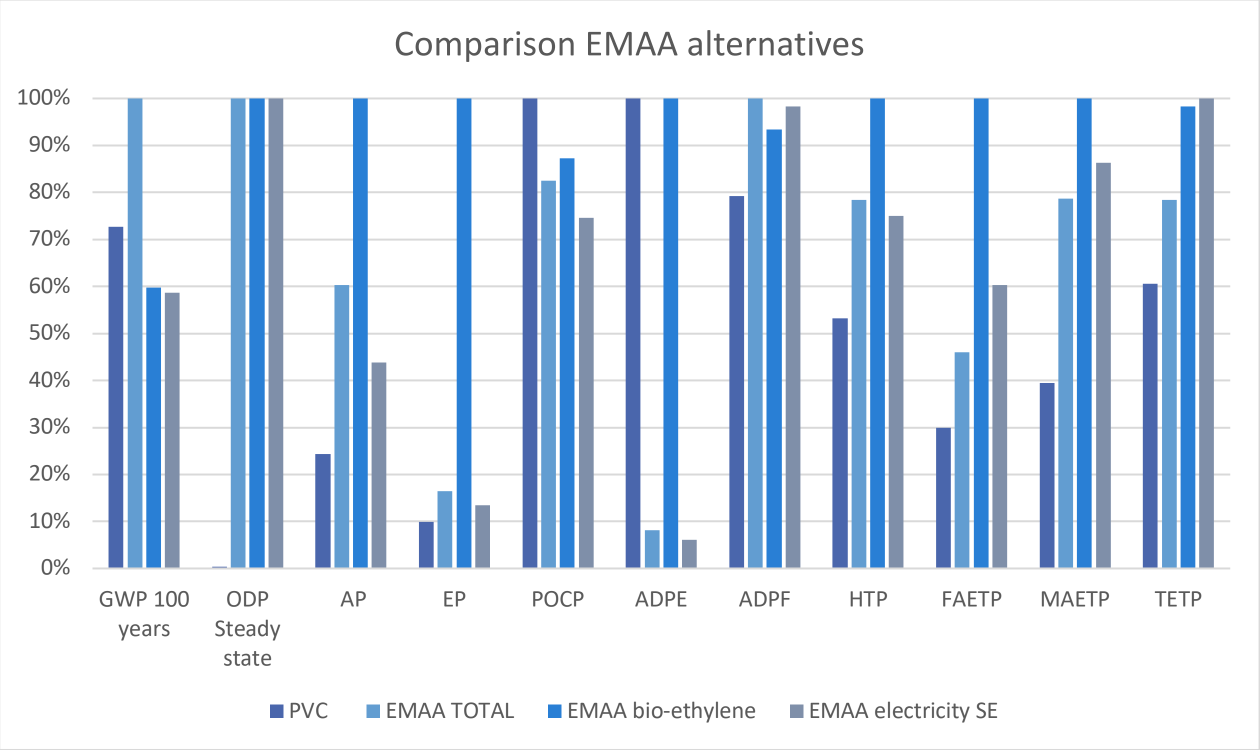

Figure 21: Comparison of the environmental impacts of EMAA with the other EMAA alternatives and PVC. The results have been converted to percentages of the impact from the polymer with highest impact in each category.

4.5.3.5 EVA

When the fossil-based ethylene was substituted with bio-based ethylene the global warming potential (GWP) was decreased with 43%, but just as in the case of EMAA, the eutrophication potential (EP) and abiotic depletion potential of elements (ADPE) were significantly increased. In the EVA polymerization the ethylene used to make vinyl acetate was also substituted with bio-based ethylene and the same trends, as when changing the ethylene in the copolymerization, were noted. Impacts that were decreased got even lower and impacts that were increased got even higher, when changing all the ethylene to bio-based. A comparison with EVA and PVC is seen in *Figure* 22*,* which shows that the GWP becomes lower than for PVC. However, EP and ADPE are much higher than for PVC and EVA.

Most of the impacts were reduced when using Swedish electricity instead of the generic European electricity mix. The only two categories that were increased were freshwater aquatic (FAETP) and marine aquatic ecotoxicity potentials (MAETP), which both increased with less than 3%.

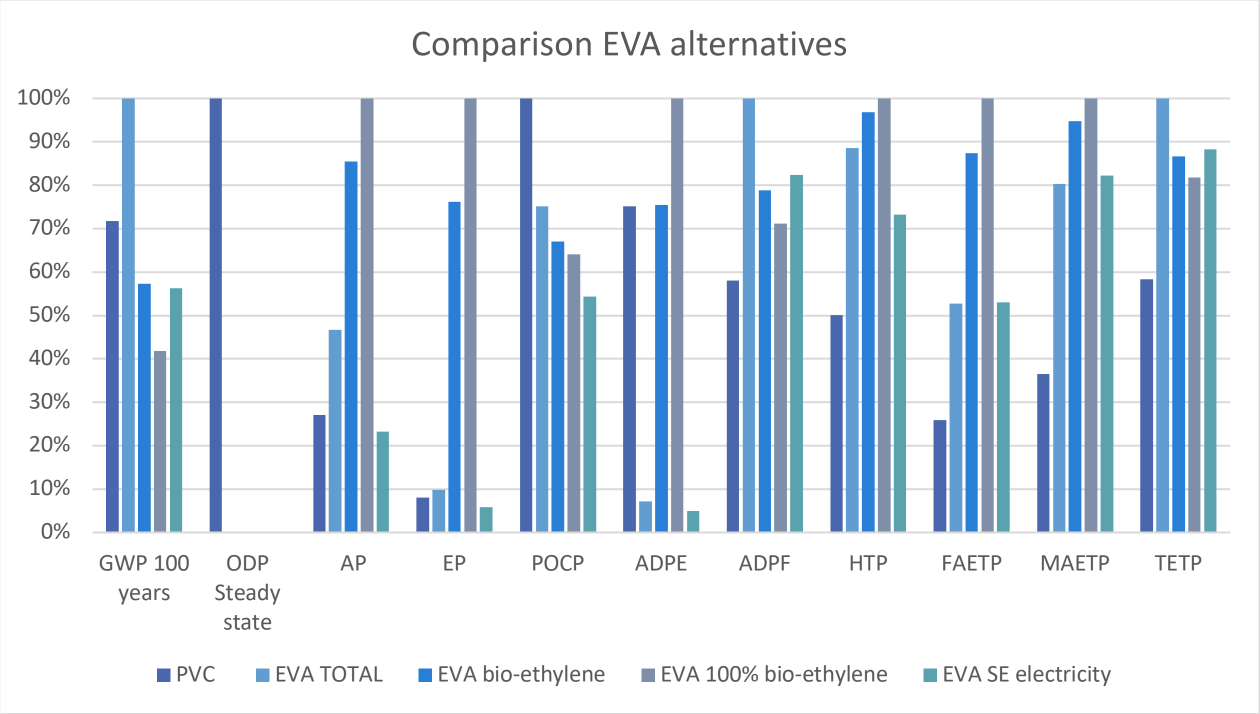

Figure 22: Comparison of the environmental impacts of EVA with the other EVA alternatives and PVC. The results have been converted to percentages of the impact from the polymer with highest impact in each category.

4.5.3.6 Comparison of the best alternatives

For the polymers that got a lower global warming potential (GWP) than PVC in the sensitivity analysis a comparison was made with PVC based on bio-based ethylene, presented in *Figure* 23. It is seen that bio-based PVC has the lowest GWP followed by EVA made from bio-based ethylene. mPPE (PS) with bio-based methanol has the third lowest GWP even if it has the highest impact when fossil-based methanol is used.

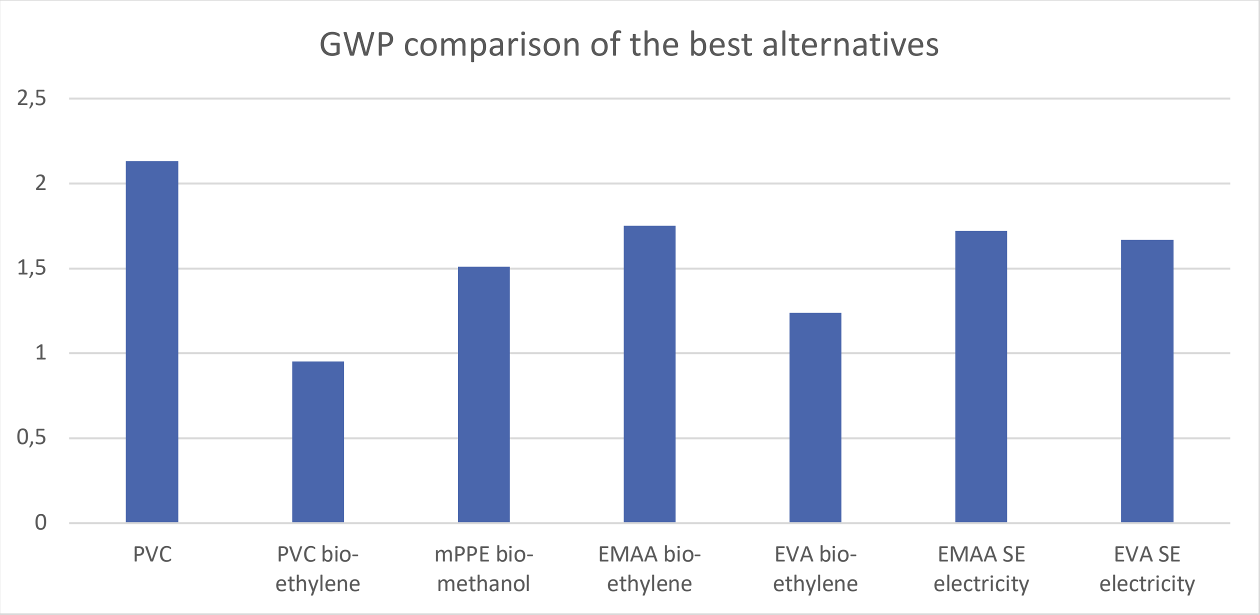

Figure 23: Comparison of the global warming potential (GWP) for the polymers that got a lower GWP-value than PVC in the sensitivity analysis.

5. Discussion

5.1 Polymers in flooring systems

The bad reputation of PVC derives from the many concerns of the human and eco toxicity previously discussed in section *2.5.2 PVC disadvantages*. During the years of manufacturing and production of PVC and its derivatives the industry has developed and optimized the processes involved. The strict regulations have also contributed to the low emissions of dioxins, VCM and VOC that the PVC industry today is contributing with. As the results conclude, none of the alternative polymers are preferable from a life cycle perspective. PVC has the best performance of both the global warming (GWP) and acidification potential (AP). If only the human toxicity potential and the eco toxicity potential are considered, PVC performs the second best after ELO.

In flooring products additives are always essential to achieve desired physical properties. The additives historically used in PVC products are also a part of the environmental drawback associated with PVC. In this study only the polymers, and not potential additives, have been examined, meaning that a conclusion cannot be drawn from these results regarding the final polymer flooring product. For example, it is likely that less amount of softeners are needed for ELO, EMAA and EVA in a flooring product compared to PVC since they are less rigid and stiff. For mPPE (PS) it depends on the proportions of the blend, in which the optimum ratio can only be determined with experimental research. Another example is that the amount of polymer needed per square meter flooring product might vary between the polymers. This would in turn affect the environmental load of the final product. To draw conclusions regarding preferred flooring systems a full cradle-to-cradle analysis must be conducted. At the present, no such products exist for the alternative polymers.

5.2 Alternative pathways

5.2.1 mPPE (PS)

The LCIA results conclude that mPPE (PS) was the polymer with the highest impact in most categories. According to the dominance analysis this is mainly due to the high environmental impact from the PPE production which is highly affected by the production of DMP. When alternative pathways of the production line were introduced, environmental benefits were noticed. The largest difference was observed when the fossil-based methanol, used in DMP production, was exchanged for bio-based methanol. The GWP decreased by 75% and was thereby lower than for PVC. This indicates that mPPE (PS) could be an interesting alternative material to PVC from an environmental perspective if it is possible to use bio-based methanol. The dominance analysis showed that PPE has a higher environmental impact than PS. It is therefore of high interest to do further research to determine the optimal proportions for a flooring product, since this will affect the results drastically. Also noted is that even if the electricity was not considered a hotspot for mPPE, Swedish electricity had a relatively high positive impact on the environmental performance, indicating that the location of the production site of the polymers is of importance.

5.2.2 ELO

The production of ELO has a higher impact on GWP than PVC, and it has significantly higher impact on ODP, AP and EP. The dominance analysis reveals that the linseed oil production dominates the impacts for AP and EP, which is expected since those categories are strongly related to agriculture of crops. The crosslinker production is the main contributor for the other impact categories. When the crosslinker was substituted with a partially bio-based one, the GWP decreased by 10% but is still higher than for PVC. Some of the impact categories had a significant increase. Even if the production of ELO has a higher impact on the GWP than PVC, it would still be of interest to further research the possibilities of replacing PVC with ELO due to its very low human toxicity (HTP) and ecotoxicity potential (ETP). In addition, it seems to be possible to make ELO 100% bio-based which is a huge advantage.

5.2.3 EMAA & EVA

The production process of EMAA and EVA are very similar and have therefore similar environmental impacts in most categories. Both EMAA and EVA scores higher than PVC for most impact categories. From the dominance analysis it is seen that the ethylene production and electricity have a high impact. The large impact of the electricity is due to the high energy demanding polymerization process. When either the electricity was substituted with Swedish or the ethylene was substituted with bio-based, the global warming potential (GWP) was greatly reduced and became lower than for PVC. This indicates that EMMA and EVA could be a good alternative to PVC depending on where the production site is located and if it is possible to use bio-based ethylene. Yet, the PVC using bio-based ethylene is still outperforming both EMAA and EVA in GWP.

6. Conclusion

To conclude, at the moment PVC is the best option from an environmental point of view at the moment, despite its bad reputation. By using bio-based ethylene for the production of PVC the global warming potential can be reduced. This was also seen for the alternative polymers where bio-based materials in the production of mPPE (PS), EMAA and EVA yielded lower GWP than for PVC. However, with biobased ethylene AP, EP and ADPE were significantly increased.

It was also seen that the location of the production of the polymers affected the results, with Swedish electricity the GWP for EMAA and EVA got lower than for PVC. From a global warming potential (GWP) perspective, these polymers perform better than PVC. However, even with the alternative pathways the GWP was not lower than for bio-PVC.

Even though ELO has a higher GWP than PVC it remains interesting for future research due to the low human- and ecotoxicity potentials and the possibility of making it 100% bio-based. ELO, EMAA and EVA are softer and more flexible than PVC, possibly mPPE (PS) as well depending on its composition, this indicates that less softeners would be needed in a product. This could lead to a lower environmental impact of the finished product compared to PVC with its additives. Although more research is needed to determine this.

6.1 Future work

Future work should include more research on the properties of the polymers to see how suitable they would be for a flooring application. That includes finding the optimal composition for the PPE/PS blend and the copolymers, EMAA and EVA, as well as finding appropriate additives for a final product. PVC has been around for a long time and the processes have been optimized, which has led to more environmentally friendly processes. This is not the case with the other polymers and with better processes it is possible that the polymers can have a lower impact on the environment compared to PVC.

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Appendix A – Dominance Analysis

Results of the dominance analysis performed on mPPE (PS), ELO, EMAA and EVA.

Table A1: Dominance analysis of impacts per 1 kg of mPPE (PS).

	GWP kg CO_2 eq	**ODP** kg R11 eq	**AP** kg SO_2 eq	**EP** kg PO_4^{-3} eq	**POCP** kg C_2H_4 eq	**ADPE** kg Sb eq	**ADPF** [MJ]	**HTP** kg 1,4-DCB/kg	**FAETP** kg 1,4-DCB/kg	**MAETP** kg 1,4-DCB/kg	**TETP** kg 1,4-DCB/kg
PPE production	63.7%	54.5%	63.1%	64.5%	69.9%	67.1%	77.4%	69.8%	77.7%	62.2%	78.2%
DMP production	36.2%	50.5%	34.2%	38.3%	33.3%	48.8%	37.5%	31.9%	18.9%	36.0%	32.9%
Diamines production	4.93%	0.95%	2.52%	4.83%	3.82%	3.70%	2.43%	2.24%	2.04%	1.42%	2.46%
Toluene production	22.6%	3.04%	26.4%	21.3%	32.8%	14.4%	37.5%	35.9%	56.7%	24.8%	42.9%

Table A2: Dominance analysis of impacts per 1 kg of ELO

	GWP kg CO_2 eq	**ODP** kg R11 eq	**AP** kg SO_2 eq	**EP** kg PO_4^{-3}eq	**POCP** kg C_2H_4 eq	**ADPE** kg Sb eq	**ADPF** [MJ]	**HTP** kg 1,4-DCB/kg	**FAETP** kg 1,4-DCB/kg	**MAETP** kg 1,4-DCB/kg	**TETP** kg 1,4-DCB/kg
Linseed oil production	38.4%	100%	87.2%	100%	69.4%	0.00%	0.00%	3.41%	0.00%	0.00%	0.00%
Crosslinker	45.7%	0.00%	7.83%	0.00%	21.4%	87.2%	66.6%	63.7%	64.2%	55.5%	41.7%
Dipropylene glycol production	19.2%	0.00%	6.63%	0.00%	17.8%	85.8%	49.9%	52.7%	62.2%	51.7%	35.9%

Table A3: Dominance analysis of impacts per 1 kg of EMAA

	GWP kg CO_2 eq	**ODP** kg R11 eq	**AP** kg SO_2 eq	**EP** kg PO_4^{-3}eq	**POCP** kg C_2H_4 eq	**ADPE** kg Sb eq	**ADPF** [MJ]	**HTP** kg 1,4-DCB/kg	**FAETP** kg 1,4-DCB/kg	**MAETP** kg 1,4-DCB/kg	**TETP** kg 1,4-DCB/kg
Methacrylic acid production	17.7%	100%	39.7%	12.1%	27.0%	0%	0%	0%	0%	0%	0%
Ethylene production	31.9%	0%	17.1%	18.7%	36.0%	30.7%	73.7%	44.0%	81.1%	22.0%	69.4%
Electricity	50.5%	0%	42.9%	43.4%	36.9%	69.0%	25.9%	55.4%	18.1%	77.8%	29.7%

Table A4: Dominance analysis of impacts per 1 kg of EVA

	GWP kg CO_2 eq	**ODP** kg R11 eq	**AP** kg SO_2 eq	**EP** kg PO_4^{-3}eq	**POCP** kg C_2H_4 eq	**ADPE** kg Sb eq	**ADPF** [MJ]	**HTP** kg 1,4-DCB/kg	**FAETP** kg 1,4-DCB/kg	**MAETP** kg 1,4-DCB/kg	**TETP** kg 1,4-DCB/kg
Ethylene production	31.5%	3.85%	0%	25.4%	39.5%	26.1%	54.0%	36.7%	61.1%	20.0%	52.4%
Vinyl Acetate production	18.9%	3.32%	13.3%	15.2%	19.9%	14.9%	26.5%	17.0%	24.6%	9.52%	24.5%
Electricity	49.8%	92.8%	61.6%	59.0%	40.4%	58.7%	19.0%	46.3%	13.6%	70.6%	22.4%

Appendix B – Sensitivity Analysis

Table B1: Sensitivity analysis of bio-based PVC using S-PVC as the benchmark.

	GWP kg CO_2 eq	**ODP** kg R11 eq	**AP** kg SO_2 eq	**EP** kg PO_4^{-3}eq	**POCP** kg C_2H_4 eq	**ADPE** kg Sb eq	**ADPF** [MJ]	**HTP** kg 1,4-DCB/kg	**FAETP** kg 1,4-DCB/kg	**MAETP** kg 1,4-DCB/kg	**TETP** kg 1,4-DCB/kg
Bio-based PVC	-55.3%	-6.68%	215%	1077%	-11.1%	-0.10%	8.45%	-	-	-	-

Table B2: Sensitivity analysis using mPPE (PS) as the benchmark. Bio-methanol based mPPE (PS), mPPE (PS) with different compositions of PPE and PS (40/60, 30/70, 10/90)) and mPPE (PS) production using German and Swedish electricity respectively were analyzed.

	GWP kg CO_2 eq	**ODP** kg R11 eq	**AP** kg SO_2 eq	**EP** kg PO_4^{-3}eq	**POCP** kg C_2H_4 eq	**ADPE** kg Sb eq	**ADPF** [MJ]	**HTP** kg 1,4-DCB/kg	**FAETP** kg 1,4-DCB/kg	**MAETP** kg 1,4-DCB/kg	**TETP** kg 1,4-DCB/kg
Bio-methanol based mPPE (PS)	-75.0%	-2.03%	-3.25%	1.68%	-5.15%	-13.7%	-18.4%	-6.98%	-0.35%	-3.96%	-11.8%
mPPE (PS) 40% PPE 60% PS	-6.80%	1.89%	-9.94%	-6.72%	-10.3%	-5.59%	-11.3%	-10.0%	-11.9%	-8.39%	-12.4%

mPPE (PS) 30% PPE 70% PS	-16.3%	-11.1%	-19.4%	-17.0%	-20.6%	-18.0%	-23.6%	-21.3%	-23.7%	-19.3%	-25.3%
mPPE (PS) 10% PPE 90% PS	-35.0%	-37.1%	-38.2%	-37.9%	-40.9%	-42.2%	-47.6%	-43.2%	-47.4%	-41.5%	-50.9%
mPPE (PS) Swedish electricity	-20.6%	-49.1%	-24.2%	-18.7%	-10.3%	-15.5%	-6.60%	-8.31%	0.18%	1.40%	-4.7%
mPPE (PS) German electricity	2.65%	14.9%	-0.51%	4.20%	0.00%	6.21%	0.94%	1.00%	0%	2.80%	0.59%

Table B3: Sensitivity analysis using ELO as the benchmark.

	GWP kg CO_2 eq	**ODP** kg R11 eq	**AP** kg SO_2 eq	**EP** kg PO_4^{-3}eq	**POCP** kg C_2H_4 eq	**ADPE** kg Sb eq	**ADPF** [MJ]	**HTP** kg 1,4-DCB/kg	**FAETP** kg 1,4-DCB/kg	**MAETP** kg 1,4-DCB/kg	**TETP** kg 1,4-DCB/kg
ELO Bio-based crosslinker	-10.9%	33.6%	3.20%	0.00%	5.20%	7056%	-49.8%	240%	1208%	-51.8%	-25.4%
ELO Swedish electricity	-1.82%	0.00%	-0.80%	0.00%	-1.30%	-0.36%	-2.73%	-3.26%	0.22%	0.56%	-0.91%
ELO Energy from biomass	-9.09%	0.00%	6.40%	0.00%	11.42%	0.73%	-20.48%	81.5%	19.6%	885%	19.8%

Table B4: Sensitivity analysis using EMAA as the benchmark.

	GWP kg CO_2 eq	**ODP** kg R11 eq	**AP** kg SO_2 eq	**EP** kg PO_4^{-3}eq	**POCP** kg C_2H_4 eq	**ADPE** kg Sb eq	**ADPF** [MJ]	**HTP** kg 1,4-DCB/kg	**FAETP** kg 1,4-DCB/kg	**MAETP** kg 1,4-DCB/kg	**TETP** kg 1,4-DCB/kg
EMAA Bio-based ethylene	-40.3%	0.00%	65.7%	506%	5.86%	1123%	-6.67%	27.6%	117%	27.1%	25.3%
EMAA Swedish electricity	-41.3%	0.00%	-27.3%	-18.6%	-9.55%	-24.8%	-1.75%	-4.31%	31.1%	9.78%	27.5%

Table B5: Sensitivity analysis using EVA as the benchmark.

	GWP kg CO_2 eq	**ODP** kg R11 eq	**AP** kg SO_2 eq	**EP** kg PO_4^{-3}eq	**POCP** kg C_2H_4 eq	**ADPE** kg Sb eq	**ADPF** [MJ]	**HTP** kg 1,4-DCB/kg	**FAETP** kg 1,4-DCB/kg	**MAETP** kg 1,4-DCB/kg	**TETP** kg 1,4-DCB/kg
EVA Bio-based ethylene	-42.8%	47.8%	83.0%	673%	-10.8%	945%	-21.2%	9.35%	65.7%	18.1%	-13.4%
EVA bio-based ethylene & vinyl acetate	-58.2%	65.1%	114%	916%	-14.7%	1284%	-28.9%	12.9%	89.5%	24.6%	-18.2%
EVA Swedish electricity	-43.8%	-80.9%	-50.4%	-40.7%	-27.6%	-31.5%	-17.6%	-17.3%	0.42%	2.42%	-11.7%

Appendix C – Calculations

DMP production

The wanted mass is 1kg and it have been calculated with 80% yield. From the source it is known that 10 times more methanol than phenol should be used. The proportions between phenol and nitrogen gas are also known.

$$m(DMP) = \frac{wanted\ mass}{yield} = \frac{1000}{0.8} = 1250\ g$$

$$n(DMP) = \frac{m(DMP)}{M(DMP)} = \frac{1250}{122.159} = 10.23\ mol$$

$$n(phenol) = n(DMP) = 10.23\ mol$$

$$m(phenol) = M(phenol) * \text{ n(phenol)} = 94.11 * 10.23 = \mathbf{963\ g}$$

$$n(methanol) = 10 * \ n(phenol) = 102.3\ mol$$

$$m(methanol) = M(methanol) * n(methanol) = 32.04 * 102.3 = \boldsymbol{3279\ g}$$

$$Proportions = \frac{n(N_2)}{n(phenol)} = \frac{0.881}{0.011} => n(N_2) = 820\ mol$$

$$m(N_2) = \text{M}(N_2) * \ \text{n}(N_2) = 14 * 820 = \mathbf{11\ 473\ g}$$

$$M(DMP) = 122.159 \frac{g}{mol}$$

$$M(methanol) = 32.04 \frac{g}{mol}$$

$$M(phenol) = 94.11 \frac{g}{mol}$$

$$M(N_2) = 14 \frac{g}{mol}$$

The catalyst was approximated to 2wt% of the theoretical mass of DMP. => **25g**

Extrusion mPPE

The energy for the extrusion was estimated to the same as for PLA. From the source it was found that 1000 containers required 2010MJ to be produced and 1kg required 65.8MJ. 283MJ was required for extrusion of 1000 containers.

$$m(1000\ containers) = \frac{2010}{65.8} = 30.55\ kg$$

$$E = \frac{283}{30.55} = 9.26 \frac{MJ}{kg}$$

ELO production

For ELO the moles for dipropylene glycol and maleic monoester were taken from the source. The yield was set to100%. For the production the proportions between crosslinker and ELO is known.

$$n(dipropylene\ glycol) = 0.775\ mol$$

$$n(maleic\ monoester) = 1.55\ mol$$

$$M(dipropylene\ glycol) = 134.17\frac{g}{mol}$$

$$M(maleic\ ester) = 98.06\frac{g}{mol}$$

$$\begin{aligned} m(dipropylene\ glycol) = {} & M(dipropylene\ glycol) * n(dipropylene\ glycol) \\ & = 134.17 * 0.775 = 104\ g \end{aligned}$$

$$\begin{aligned} m(maleic\ monoester) = {} & M(maleic\ monoester) * n(maleic\ monoester) \\ & = 98.06 * 1.55 = 152\ g \end{aligned}$$

100% yield gives 0.775 mol crosslinker and

$$\begin{aligned} m(crosslinker) = {} & m(dipropylene\ glycol) + m(maleic\ monoester) = 104 + 152 \\ & = 256\ g \end{aligned}$$

$$n(ELO) = \frac{n(crosslinker)}{2} = \frac{0.775}{2} = 0.3875\ mol$$

$$M(ELO) = 975.4\frac{g}{mol}$$

$$m(ELO) = M(ELO) * n(ELO) = 975.4 * 0.3875 = 378\ g$$