COMPARATIVE LIFE CYCLE ASSESSMENT OF A SUSTAINABLE MODULAR TINY-HOUSE

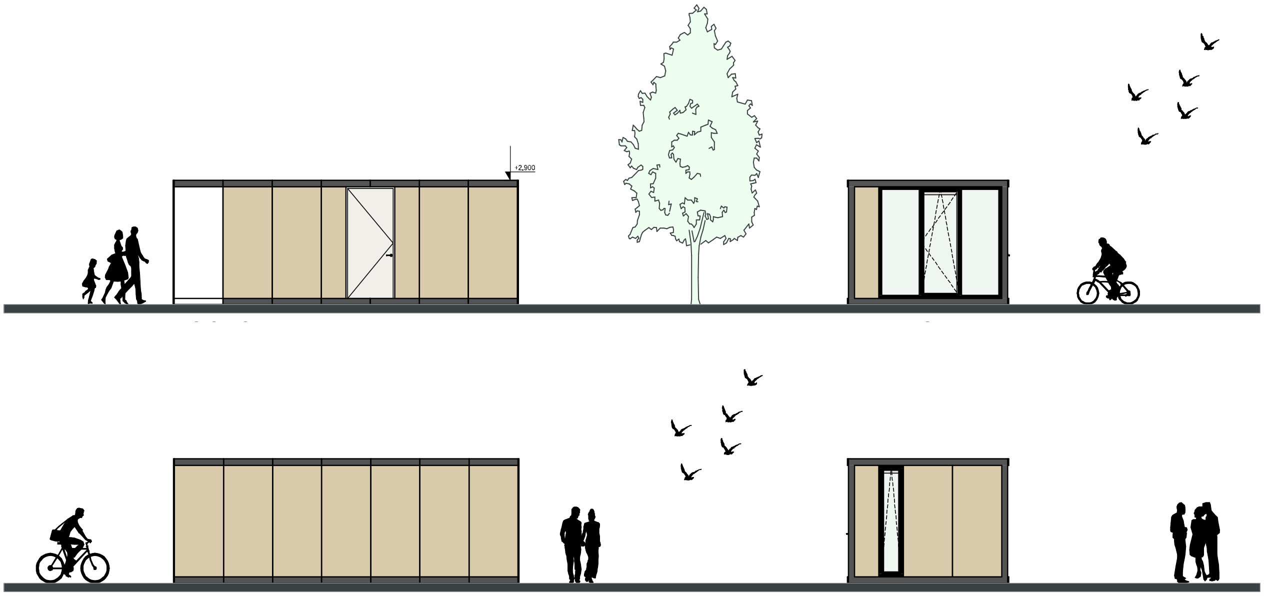

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Table of Contents

1 Abstract

Climate change presents a big challenge to the construction industry, which is responsible for a big fraction of total emissions. Conducting a comparative life cycle assessment (LCA) for a building in the design phase provides useful findings which can be used to change the design to reduce emissions. In this thesis, a comparative LCA for a modular tiny house is done. Twelve alternative designs are created, where in each alternative design one material is changed. The alternatives are compared through seven environmental indicators: global warming potential, ozone depletion potential, acidification potential, eutrophication potential, photochemical ozone creation potential, abiotic depletion potential of non-fossil fuel resources, and abiotic depletion potential for fossil fuel resources. Combining the original and alternative designs, there are four materials for the sheathing: laminated veneer lumber (LVL), oriented strand board (OSB), magnesium board (MgO), and fibre cement, three for the insulation: EPS, XPS, and PU, three for the roof membrane: PVB, PVC, and bitumen, and six for the façade cladding: wood, basalt, composite stone, slate, aluminium, and fibre cement. The results from the LCA have shown that for the sheathing material, OSB and LVL scored the best for all indicators, while fibre cement scored the worst. For the insulation EPS scored the best in all indicators but photochemical ozone creation potential. For the roof membrane, all three solutions had similar indicator scores, apart from the increased ozone depletion potential for PVC. For the façade, the wood, slate, and fibre cement scored similarly for all indicators, while composite stone scored the worst. It can be seen from the LCA analysis that there is no simple solution for the best design alternative, and therefore the developed LCA model in this research can be used as a support in decision making during the design stage.

2 Terms, definitions, and abbreviations

(Environmental) indicator – A measure for a specific environmental effect, such as global warming or eutrophication.
Sheathing – The outer core of a structural insulated panel (SIP). Other names are commonly used for this component, such as structural skin or structural panel, but in this report, the term sheathing is used.

HVAC – Heating, ventilation, and air conditioning
SIP – Structural insulated panel. A type of sandwich panel that has great structural and insulating properties. Composed of a rigid insulation core sandwiched between two layers of structural sheathing.
EPD – Environmental product declaration. EN 15804+A1 (2013) abiding EPDs are the main source of environmental impacts used in this LCA.

<u>Environmental indicators</u>
GWP – Global warming potential
ODP – Ozone depletion potential
AP – Acidification potential
EP – Eutrophication potential
POCP – Photochemical ozone creation potential
ADPE – Abiotic depletion potential for non-fossil fuel resources
ADPF – Abiotic depletion potential for fossil fuel resources

<u>Materials</u>
LVL – Laminated veneer lumber.
OSB – Oriented strand board.
MgO – Magnesium oxide. In this report MgO will often be used to refer to magnesium oxide boards.
EPS – Expanded polystyrene.
XPS – Extruded polystyrene.
PU – Polyurethane. In this report PU will often be used to refer to polyurethane rigid insulation boards.
PVC – Polyvinyl chloride.
PVB – Polyvinyl butyral.

3 Introduction

This thesis concerns a comparative life cycle assessment for a tiny modular house. The comparative aspect is the comparison between alternative designs, where in each alternative design one material is changed. In this way it is possible to determine how the alternatives designs affect the environmental scores relative to the original design, with the objective of finding possible improvements to the original design. To complete this objective, this project has one main research question, what are the environmental indicator scores for the original Forest Living house and the alternative designs? In this case, the environmental indicators are the 7 main ones as per EN 15804 A1, these are listed and explained in chapter 4.4.

This project was commissioned by *Forest Living*, a start-up company based around constructing environmentally friendly houses. However, the work for the company had to be discontinued, which meant the scope of the project was narrowed down. Since most inputs were known before the cessation of work for the company, this allowed for the continuation of the project. The only inputs which had to be excluded were the energy use for the assembly of the Structural insulated panels (SIPs), and the energy and use of ancillary materials for the assembly of the house. The work continued at Infra Plan Consulting company, with the extensive expertise in sustainability topics of structures and life cycle analysis.

This report has the following structure. First, the goal and scope are going to be defined in chapter 4, including the limitations, the assumptions, the methodology, the description of the object of assessment, and other details which explain how the LCA was achieved. Second, chapter 5 will deal with the life cycle inventory, this will explain the materials for which data was collected, data which is used to create the results, which are outlined and explained the following chapter, chapter 6. After, the results are interpreted in chapter 7, here a discussion of the results is complemented with recommendations. Finally, chapter 8 finalizes the report with a conclusion.

4 Goal & Scope

4.1 Goal

The goal of this study is the comparison of the environmental performance of different designs solutions for a modular tiny house, through a comparative whole building life cycle assessment (LCA). The original design of the house will be compared to alternative designs, where one material is changed, e.g. the LVL SIP sheathing is changed to OSB. This comparative LCA will be done for the whole life cycle of the building, from cradle to grave.

The LCA is focused on the comparison of products within the context of the analysed building, it is not the goal of the study to provide a whole picture of the total environmental impact of the house throughout its lifetime. Thus, the results of this study are not intended to be used in a comparative assertion against other houses.

The intended audience of this study is meant to be the client, who is responsible for designing and manufacturing the house, which is the object of this study. Other designers can use the information of this study to make sustainability-oriented decisions in the design process, but they must understand that the context of this building is very specific: a modular tiny house. The main aim is to communicate to the client which alternatives are possible, and what environmental impact these alternatives have relative to the original design.

The LCA analysis performed in this research is following the framework outlined in the European standard code, EN 15978, which explains how to perform an assessment of the environmental performance for buildings. ISO 14040, which outlines the requirements for conducting LCAs, is also used as a guide for development of the structure of this report.

4.2 Study scope

This sub-chapter is split into four sections. First, the product system is going to be defined, explaining the life cycle of the building and what is and what is not within the system boundary of this study. Second, the object of assessment, the tiny modular house, is going to be specified, to provide transparency on the estimation of the quantities of materials from which the results are derived. Third, the functional equivalence is going to be defined. This section also includes an explanation on how the functional equivalence was integrated with respect to the structural and energy use context. Finally, the system boundaries are going to be defined more clearly, by going through each life cycle stage individually.

4.2.1 The product system

The product system is a collection of interconnected processes that describes the life cycle of a product. The product system is useful in defining the boundaries of the study, by explaining which processes are included and excluded. In this study, the product system is the cradle-to-grave life cycle of a modular tiny house, whose specifications will be explained in the next subchapter. The next paragraphs will briefly explain the product system, whereas chapter 4.2.4, System boundary, will expand on this chapter by explaining how each life cycle stage was included with greater detail. Figure 1 illustrates the product system.

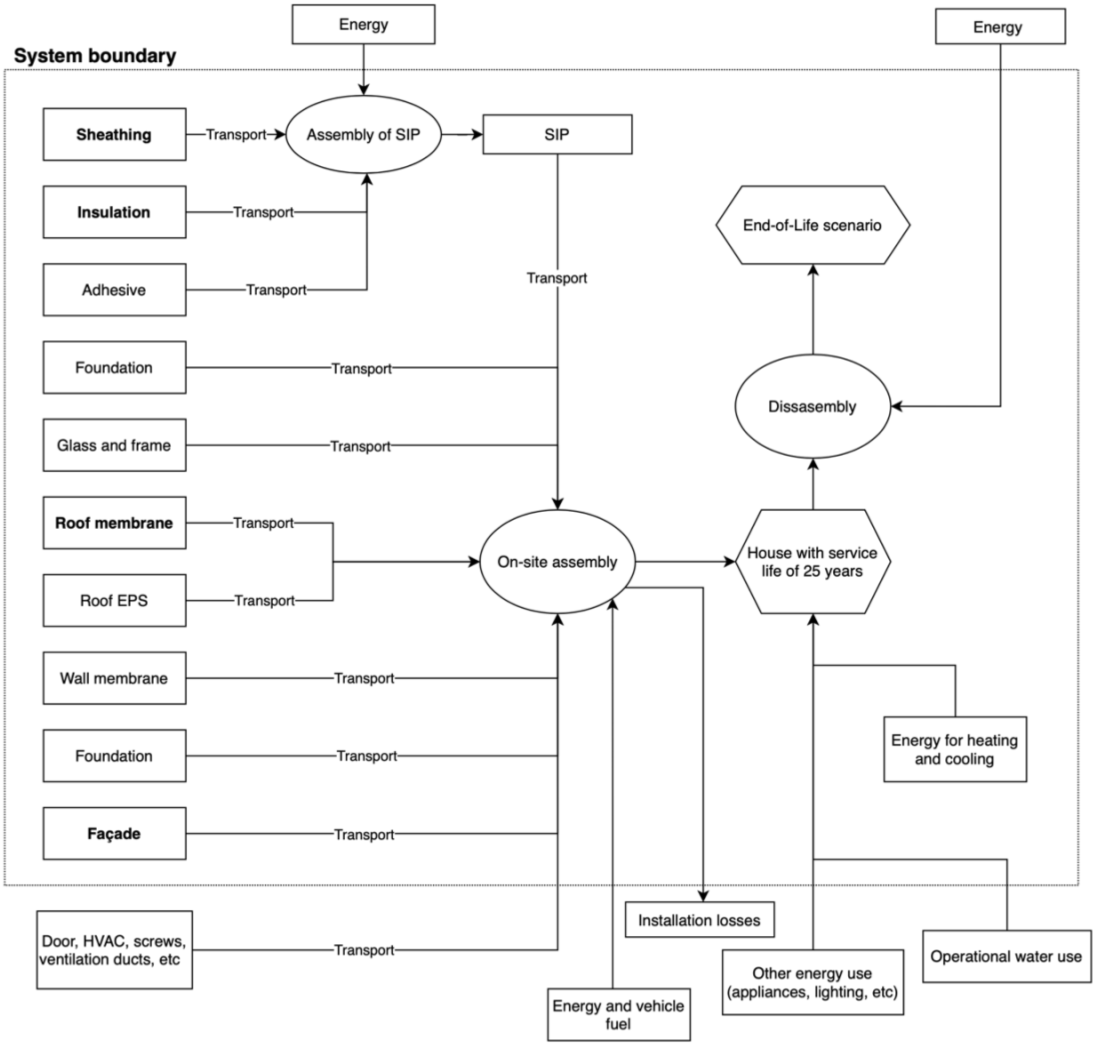

Figure 1 Product system diagram

To start, the product system considers the embedded costs for part of the products which are necessary to assemble the house. Including all products was beyond the scope of this study, as the boundaries were drawn by the availability of the EPDs. Next, the transport costs for the products are considered, an average transport distance for the Netherlands is assumed. For the sheathing, insulation and adhesive, an extra haul is assumed, since these products first travel to the factory, where they are assembled into structural insulated panels (SIPs). The energy costs for assembling the different combinations of the SIPs are out of the boundary of this study, it is assumed that the energy costs are similar for all combinations.

For the on-site assembly, no processes were accounted for, as they could not be estimated due to the cessation of work with the client. Installation losses, use of ancillary materials, material and energy use necessary for the construction process, and all other processes required as per EN 15978 are out of the boundary of the system.

The heptagon in the diagram represents the use stage. Only the energy for heating and cooling is included in the boundary, this will make it possible to see how the different insulation and sheathing materials will impact the energy use throughout the 25 years of service life. It is assumed no repair, maintenance, replacement, and refurbishment will be needed, since no products used in this assessment have a service life under 25 years. The operational water use and the energy use for things which are not heating and cooling, such as appliances and lighting, are outside the boundaries of the system. Lastly, the costs of the process of disassembling the house, after its 25-year service life, is out of the boundaries of this study.

4.2.2 Specification of the original house design

This subchapter will outline the specifications of the object of assessment, in terms of its physical characteristics. It is important to note that object of assessment is an unfinished design, the structural connections are missing, and the material use is not minimized. This subchapter will provide transparency on the estimation of materials used in the house, which can be seen in Appendix A, Table 12. This specification is only for the elements of the house which are within the boundaries of the assessment.

4.2.2.1 Superstructure

The house has a length of 8.4 m, a width of 4 m, and a height of 3.2m, excluding the roof, a depiction of the house can be seen in Figure 3. The building blocks of the house are the SIPs, they can be seen in Figure 4 and Figure 2, for the walls they are made of two 24mm layers of LVL sheathing and a 150mm EPS insulation core. While for the roof and ground the sheathing has the same thickness, while the insulation core is 250 mm.

The SIPs are assembled in factory with a layer of glue 0.125 mm thick for the connection between the insulation and sheathing. With this it is possible to estimate the total volume of glue used in the house.

Furthermore, the house has two triple glazed windows of 4mm thickness for each pane. A large 2.6 m high and 2.6 m wide window, and a smaller 2.6 m high and 0.6 m wide window, both measurements include the frame. Finally, there is a 2.4 m high and 1.1 m wide door, including the frame.

On the outside of the wall, the house is covered in a wall membrane for water protection. This membrane is covered in a façade cladding, made of wood for the original design.

Figure 2 Structural insulated panel, note that those used in the design have a much thicker foam core

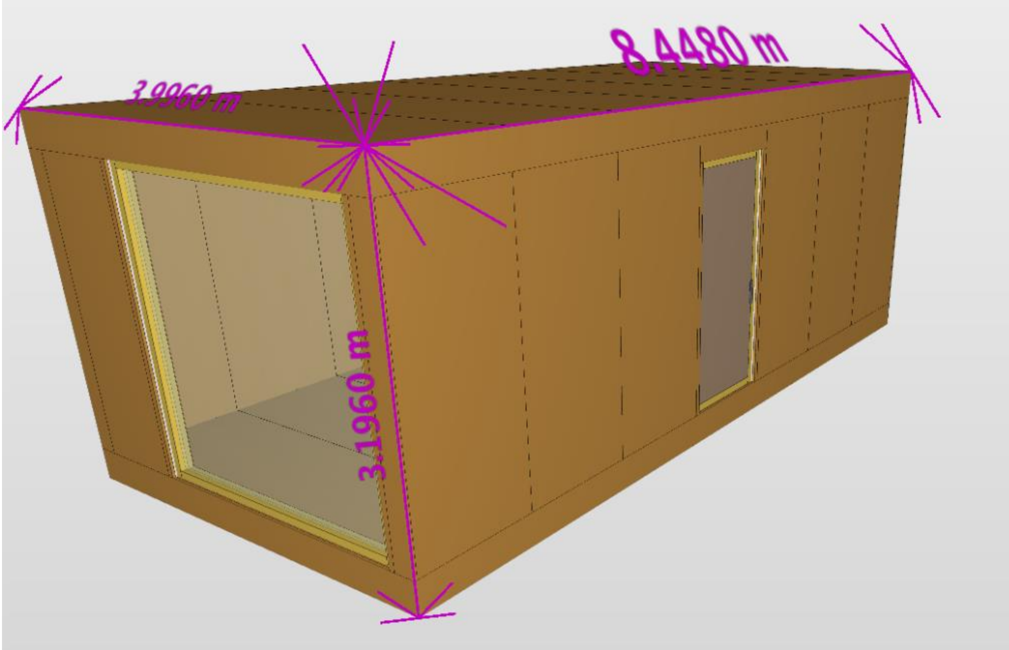

Figure 3 BIM depiction of the house

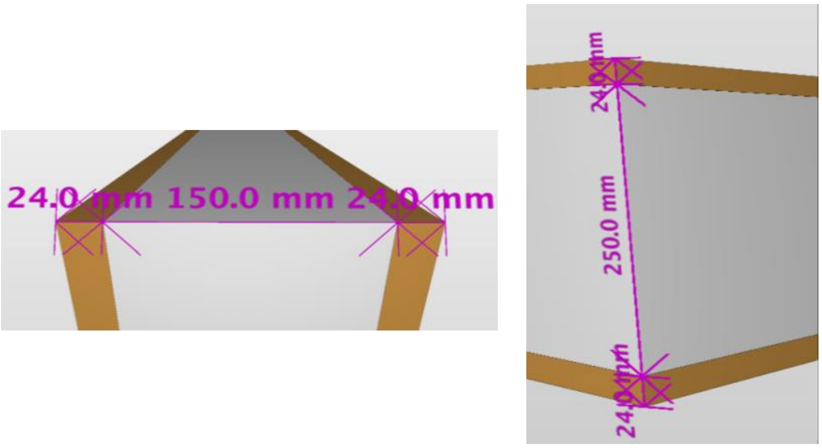

Figure 4 cross section of SIPs, on the right for wall sections, and on the left for ground and roof sections

4.2.2.2 Foundation

The foundation is composed of steel beams and special foundation screws. Figure 5 illustrates the foundation. The section on the left illustrates the foundation as viewed from the side, an L beam with height 50 mm and width 100 mm, illustrated in red, attaches to the house and to the HEA 100 beam bellow, illustrated in blue. To this H beam a foundation screw of length 1.6 m is attached. The section on the right of Figure 5, illustrates the view from the top, the foundation beams run across the perimeter of the house, the crosses represent the location of the screws, being separated approximately 2 metres from each other. The weights of the beams were extracted from Tabellen by R. Blok, whereas the weight for the foundation screws is known from the manufacturer.

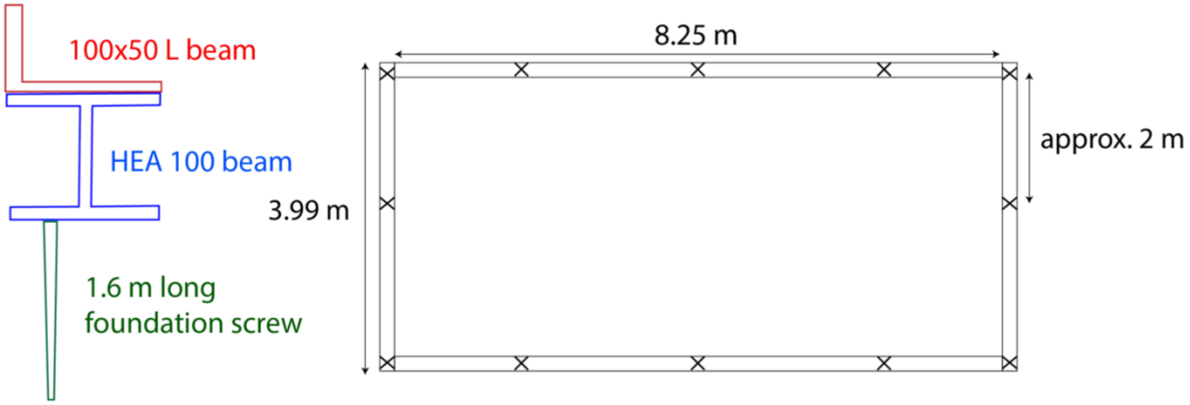

Figure 5 Foundation illustrated

4.2.2.3 Roof

To achieve drainage, an EPS layer is put on top of the roof to achieve an angle of 6 degrees. This EPS layer is bound by SIPs of the same width as the wall. This EPS is of a lower density relative to the EPS in the SIPs, as its main purpose is to provide drainage. Figure 6 illustrates the cross section of the roof, the red lines indicate the surface upon which the roofing membrane is going to be placed. The side of the SIPs that is looking away from the house are considered to be part of the wall, and is going to be fitted with façade cladding and wall membrane.

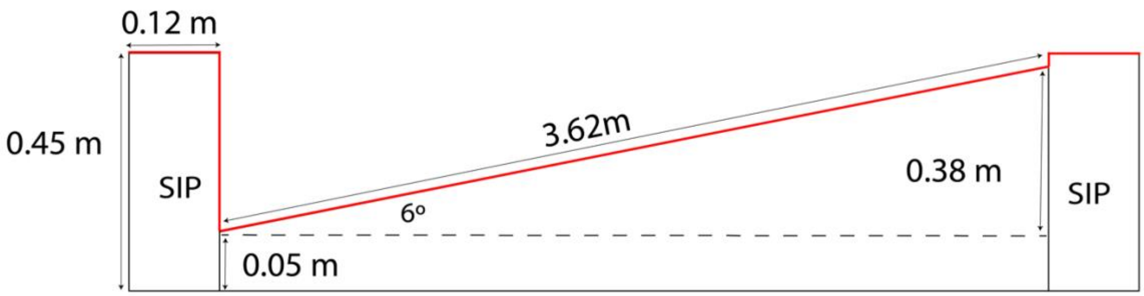

Figure 6 Cross section of roof, not to scale

4.2.2.4 Plumbing

The client provided an estimate on the necessary piping for the supply and drainage of the plumbing system. For the supply, 25 m of polybutylene pipes with a diameter of 15 mm will be needed. For the drainage, PVC pipes are used, 15 m and 20 m for pipes with diameter 110 mm and 75 mm respectively.

4.2.3 Functional equivalence

The functional equivalency is the specification of the required technical characteristics for the object of assessment. The specification for the functional equivalence relevant for this assessment can be summarised as "*A house with a service life of 25 years, that through its lifetime maintains an inside temperature of 18 degrees and remains structurally stable*". In this assessment, there is an emphasis on comparing different sheathing and insulation materials, these materials will differ in structural and insulation properties, so it's important to account for that. This subchapter is split into two parts, first explaining how structural equivalence is calculated, then explaining how energy use for the insulation is calculated.

4.2.3.1 Structural design requirements

As per EN 15978, comparisons of alternative designs for a building must be done based on their functional equivalence. A comparison between different setups for the structural insulated panels (SIPs) needs to consider the structural equivalence of the setups. In this case only the sheathing (the outer layers of the structural insulated panels) will be considered since the structural properties of the alternative insulating foam cores are similar, and they contribute only a small part of the structural stability of the SIP.

The original design in the house uses the same thickness for the sheathing throughout all SIPs, as this is more convenient for the production process. Thus, in the same way that the original design uses the same thickness for the sheathing of the SIP throughout the whole house, the alternative designs will also have the same sheathing thickness, only this thickness will change depending on the alternative`s structural equivalence to the original design.

The calculation for the structural equivalence is done using an equation for a beam, without making a distinction for wall sections. This is because, according to the client, the SIPs that must sustain the most force are the floor SIPs. Since the floor and the wall have the same thickness, and finishing the structural design to minimise material use is outside the scope of this study, the calculation relies on the equation for a beam.

To determine structural equivalence the equation for the deflection in the middle, for a beam with both ends fixed and subject to a q-load, δ_m, and the equation for the moment of inertia for a rectangular cross section, I, will be used.

$$\delta_m = \frac{1}{384}\frac{ql^4}{EI}$$

$$I = \frac{1}{12}bh^3$$

$$\delta_m = \frac{12}{384}\frac{ql^4}{Ebh^3}$$

To attain structural equivalence, the deflection in the original design ($\delta_{m;1}$) must equal the deflection in a given alternative design ($\delta_{m;2}$).

$$\delta_{m;1} = \delta_{m;2}$$

$$\frac{q_1 l^4{}_1}{E_1 b_1 h^3{}_1} = \frac{q_2 l^4{}_2}{E_2 b_2 h^3{}_2}$$

Since the designs will be subject to the same force (q), and have the same length (l) and width (b). These can cancel out from the equation, leaving:

$$E_1 {h_1}^3 = E_2 {h_2}^3$$

Since the modulus of elasticity (E), for LVL (the sheathing of the original design) and the thickness (h) is known, this relationship allows us to calculate the structurally equivalent thickness for different materials, given their modulus of elasticity. The results for the different materials are outlined in Table 1 and depicted in Figure 7.

Table 1 Structural equivalence of sheathing materials, thicknesses have been rounded up

Material	**Young's modulus (N/mm^2)**	**Thickness (mm)**
LVL	8 300	24
OSB	3 500	33
MgO Board	4 317	30
Fibre Cement	14 000	21

The selected thicknesses used for the material quantification have been rounded up, since finding structural boards with thickness such as 29.84 mm is not possible. It is also important to mention that the selected Young's modulus for the LVL was the value for only one of the selected LVL products, by Kerto, which is the LVL used by the client. This is done instead of averaging the young's modulus of all three selected LVL products. As for OSB the two selected products had the same Young's modulus, and for fibre cement only one product was selected. Finally, the selected MgO board wasn't fit for structural applications, thus the young's modulus of a structurally able MgO board was used instead.

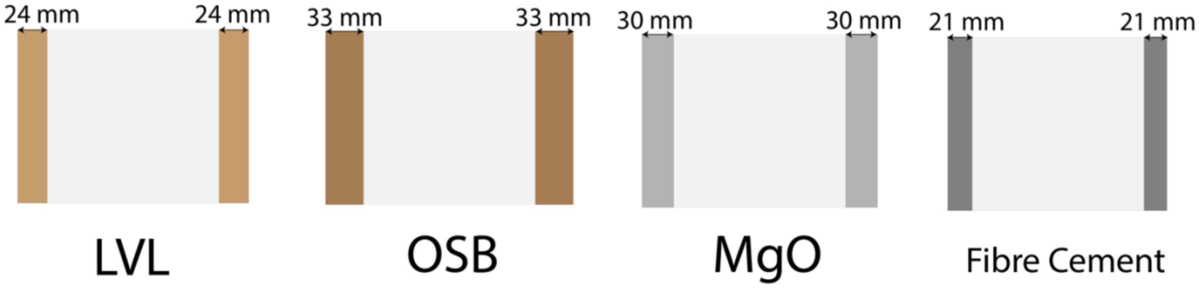

Figure 7 Illustration of the structurally equivalent SIPs, note that the insulation core remains the same thickness

As for the structural equivalence of the insulation boards, due to their very small, relative to the sheathing, young's modulus, and comparable compressive strength, they are assumed to be structurally equivalent for the same thicknesses.

4.2.3.2 Energy use model

The client developed a calculation tool, abiding Dutch standards, to calculate the energy use for heating and cooling given the specifications of the house and other details.

This tool only considers the door, triple glazed glass, window frame and the SIPs for the wall, roof, and ground. It doesn't include the cladding, the EPS located in the roof, or the finishing inside the house. The tool assumes that a steady temperature of 18 degrees inside the house is maintained all the time. Also, the energy use model takes as input the temperature patterns of the Netherlands to calculate how much heating and cooling will be necessary.

The energy use model is not used to calculate the thickness needed for the alternative insulation materials to match the insulating properties of the original design. Instead, it considers the same thickness for the insulation for all materials, thus yielding different energy expenditures depending on the material choice for the SIP. As for the thickness of the sheathing, the results from the previous part are used. So, the thicknesses for the different sheathing materials calculated for the structural equivalence, correspond to the thicknesses used in the energy use model.

To model the original and alternative designs a few parameters in the energy use model were changed. These parameters were following: the thickness of the sheathing, the R-value of the sheathing, and the R-value of the insulation. Every other input, such as the thickness of the insulation and the U-value for the windows, remained the same for all design alternatives.

4.2.4 System boundary

This section will explain the processes that are taken into account in the assessment. As per EN 15978, a new building shall include the building life cycle modules illustrated in Figure 24, in Appendix A. But before diving into this, the geographical and time boundaries must be defined.

For the geographical boundaries, this building is located and assembled in the Netherlands, thus European EPDs where prioritized in the selection process, and other processes such as transport and energy were incorporated with this in mind.

As for the time boundaries, the selected EPDs are representative for the 2010-2020 period, it doesn't go beyond 2020 since some EPDs are expired. EPDs are usually released with a 3-5 year validity period, however using only valid EPDs greatly reduced the availability of products which could be included in the assessment.

The following sections will explain how each life cycle module was included, or why it was excluded, emphasizing the data source and the assumptions.

4.2.4.1 Product stage (A1-A3)

The embedded costs of a material are accounted for in the modules A1 to A3, see Figure 24. These explain the environmental impact for the gathering of raw materials (A1), transport to manufacturing facility (A2), and manufacturing stage (A3).

The data source for this stage was pulled from EPDs, for some products the results where aggregated to form a product average. For example, for LVL three EPDs where found, attention was put that the products where similar to each other, such as their geographical scope and material properties. Then, the results of the product stage where simply averaged to form a product average.

For some wooden products, such as the LVL or OSB sheathing the global warming potential indicators are negative for this stage, this is because of the biogenic carbon stored in the wood. This LCA uses the -1/+1 method for calculating biogenic carbon, meaning that the biogenic carbon has a negative impact on the global warming potential during the product stage, since the wood stores CO2. However, in the EoL all the biogenic carbon is released back into the atmosphere, whether it is because the wood is used in energy recovery or through decomposing in a landfill.

4.2.4.2 Transport to site (A4)

Transport is modelled by using the GaBi process for trailer truck. The specific trailer truck is that with a 27 ton payload capacity and with the emission standard Euro 4. The weight of the payload in the truck is assumed to be 11756 kg for all hauls, as this is the average payload weight for the Netherlands in 2015 (Ligterink, 2015). This amounts to a 43.54% utilization rate for the chosen truck. GaBi's truck process was changed to accommodate to a Dutch scenario, meaning the share of the haul happening in a motorway, rural and urban road was 86.9%, 8.3%, and 4.8% respectively (Ligterink, 2015).

It was assumed that each product was brought by separate hauls of 150 km each. This distance is arbitrary, being representative of the distance between Zwolle and Rotterdam. To better represent the manufacturing of the SIPs, the materials for the SIPs are assumed to travel separately the 150 km, but then an extra haul of 50 km is included for all materials combined, to represent the haul of the SIPs between factory to building site.

It is assumed that no loss of transportation happens, and the transportation of construction equipment is excluded.

4.2.4.3 Installation/assembly (A5)

In the context of this building the installation and assembly process are as follows. The adhesives, sheathing, and insulation are first assembled into SIPs in the factory, then they are installed on-site along with all the other materials.

It was not possible to include this module given the cessation of work with the client, thus it was excluded completely. However, since this assessment focuses on comparing products, excluding this module leaves the question of whether some products have a much greater impact in this stage. Thus, there is an assumption that all different designs have similar impact in the installation and assembly phase. For the sheathing and insulation, only materials which are possible to assemble into SIPs in the factory setting of the client are considered, and while it may cost more energy to cut a fibre cement sheet than an OSB sheet, the difference is assumed to be negligible relative to the total impact of the building. The same is assumed for the roof membrane and façade products. It is also assumed that the same amount of glue is needed to assemble all SIP combinations.

4.2.4.4 Use stage (B1-B7)

The use stage addresses the period between the completion of the construction and the de-construction of the building. It includes the impacts from building components (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy use (B6), and operational water use (B7).

In this assessment only the energy use for heating and cooling are considered, which are part of the B6 module, as this is necessary for a fair comparison of insulation products. Modules B2 to B5 are not relevant for this assessment, as no products have a service life lower than the 25 years required service life of the house. And while for some products the EPD does specify if maintenance is needed, in all cases the maintenance cycle is longer than 25 years.

The energy for heating and cooling, which is part of B6, will be calculated using the energy use model, explained in chapter 4.2.3.2. The environmental indicator scores for energy are pulled from GaBi, the electricity grid mix process representative for an average of the Netherlands in 2016. The energy carrier mix of this GaBi process is depicted in Figure 8.

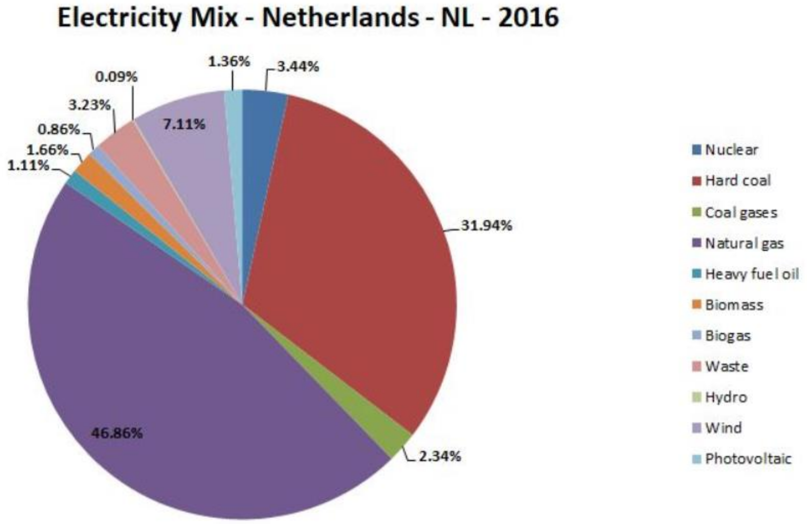

Figure 8 Energy carrier mix from the GaBi process

4.2.4.5 End-of-Life (C1-C4)

The end-of-life stage starts when the building is decommissioned. It includes the deconstruction (C1), transport (C2), waste processing for reuse, recovery, or recycling (C3), and disposal (C4).

For C2 it is assumed each disassembled product rides separately in a truck with the same specifications as the A4 module. A distance of 50 km is assumed for each haul.

The material and energy costs for deconstruction are excluded. It is assumed that the SIPs are disassembled back into sheathing and insulation, with the traces of glue not making any impacts for this stage.

The source of this life cycle stage came from EPDs. Each EPD declares one or a set of different EoL scenarios, for when an EPD declared more than one scenario, only one was selected, based on the criteria of which scenario had the least global warming potential when adding C3, C4, and D. This was considered to be the best-case scenario.

4.2.4.6 Benefits and loads beyond the system boundary (D)

This module considers the re-use, recycling, and energy recovery beyond the system boundary. As an example, energy recovery is assumed for LVL. While for C3 the indicators are positive, since burning wood causes emissions, module D considers the fact that by burning the LVL we are replacing the burning of coal, thus the indicators of module D are negative since the impacts of burning coal are avoided by burning the LVL instead. In the same fashion, for re-use, the indicators are negative since by re-using the product the resource and energy cost of manufacturing a new product are avoided.

4.3 Methodology

This section will explain the methodology employed to perform this study, since it is only partly explained in the previous sections.

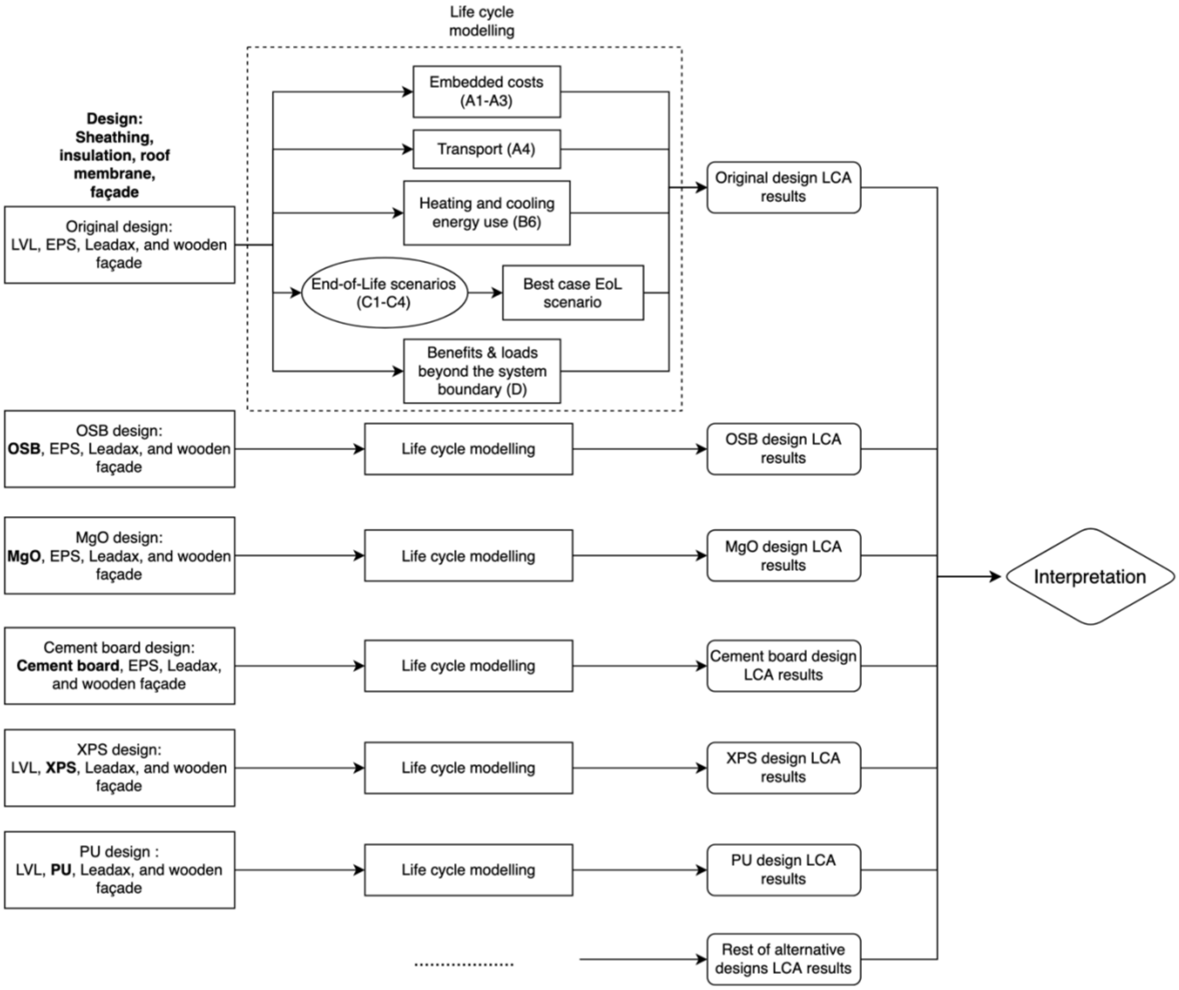

Figure 9 Methodology diagram, note that not all 13 designs are included in this diagram

Figure 9 illustrates the basics of the approach employed to perform the comparative life cycle assessment. The original design, the design which the client formulated, is going to be compared to 11 alternatives. For each alternative one product choice for a material type, sheathing, insulation, roof membrane or façade cladding, is changed. The way all alternatives are setup is explained in Table 2.

Table 2 Explanation of all designs for the comparative assessment

Design	**Sheathing**	**Insulation**	**Roof membrane**	**Façade**
Original	LVL	EPS	Leadax	Wood
OSB	**OSB**	EPS	Leadax	Wood
MgO	**MgO**	EPS	Leadax	Wood
Cement board	**Cement Board**	EPS	Leadax	Wood
XPS	LVL	**XPS**	Leadax	Wood
PU	LVL	**PU**	Leadax	Wood
PVC roofing	LVL	EPS	**PVC**	Wood
Bitumen roofing	LVL	EPS	**Bitumen**	Wood
Basalt façade	LVL	EPS	Leadax	**Basalt**
Composite Stone façade	LVL	EPS	Leadax	**Composite stone**
Slate façade	LVL	EPS	Leadax	**Slate**
Aluminium façade	LVL	EPS	Leadax	**Aluminium**
Fibre Cement façade	LVL	EPS	Leadax	**Fibre Cement**

For each alternative, and the original design, life cycle modelling is performed. This is the stage where each life cycle stage is calculated, what constitutes part of the life cycle stage was already explained in chapter 4.2.4. The life cycle modelling generates results, which are then interpreted through a discussion in chapter 7.

In the previous section, environmental product declarations (EPDs) are often mentioned. This is the source for the environmental impact for most components of the building, with the exception being transport and energy, which are retracted from GaBi. EPDs are the preferred data source for conducting a whole building LCA according to EN 15978. As of the date of the publishing of this work, EPDs are undergoing a change, from the EN 15804+A1 (2013) to the EN 15804+A2 (2019) standard. The declared indicators for these two standards are not comparable, and there is lack of EPDs for the newer standard. Because of this only EPDs from the older standard are used.

EN 15804+A1 contain three environmental indicator categories: environmental impacts, resource use, waste, and output flows. Environmental impacts is the only indicator category included in this study, which are explained in the next sub-chapter.

A final note on the use of EPD data, is that this LCA was drawn by the availability of the EPDs relevant to the house. Products, systems, and services which could have a noticeable effect on the total environmental impact of the house, such as the HVAC system, and the impact of the installation services, are not included in this LCA because of the unavailability of EPDs. But this is not considered to be a problem for this study, since the main goal of is to compare products in the context of this building, not to have a whole picture on the impacts of the building.

4.4 Environmental impacts indicators

Following environmental impact indicators will be used for the evaluation of design alternative environmental performance:

Global warming potential
This is a measure for greenhouse gas emission, that exacerbate the greenhouse effect. This indicator is reported with the unit of kilograms of CO_2 equivalent. Gases are converted to their CO_2 equivalent, for example, 1 kg of methane has a global warming potential of 27.9 kg CO_2 equivalent. This means that 27.9 kilograms of CO_2 traps as much heat as 1 kg of methane. Contributions to global warming potential can come from either fossil or biogenic sources, such as burning coal or wood.

Ozone depletion potential
This relates to the emissions that contribute to the degradation of the ozone layer, which causes higher levels of ultraviolet B rays to reach the surface of the earth, causing detrimental effects on the planet and its inhabitants. ozone depletion potential is measured in kilograms CFC-11 equivalent, CFC-11 is a refrigerant that is tightly regulated in most countries.

Acidification potential
A measure of emissions that acidify the environment, causing acid rain and other negative consequences. It is measured in kilograms sulphur dioxide (SO_2) equivalent, sulphur dioxide molecules have a great capacity to increase the ion hydrogen concentration in water, decreased pH, thus causing acidification. How well other compounds can do this, decides what SO_2 equivalent value they obtain.

Eutrophication potential
This is a measure of nutrient enrichment due to emissions, which causes changes to aquatic and terrestrial environments due to shift in species composition due to elevated biomass production. Measured in kg phosphate ($[PO_4]_3$) equivalent, the most important eutrophication potential causing compounds are nitrogen and phosphorous.

Photochemical ozone creation potential
A measure of emissions which causes smog formation in the ground level, which is harmful to living beings. This indicator is largely caused by transport and coal burning, which exacerbate a complicated natural process, resulting in smog formation. The unit for this indicator is kg ethane equivalent.

Abiotic depletion potential for non-fossil fuel resources
A measure of the depletion for non-renewable non-fossil fuel resources, decreasing their future availability. It is measured in kg antimony (Sb) equivalent, a mineral whose extraction is slowing down, as it is getting harder to find new deposits. How other resources are transformed into kg Sb equivalent is a tricky subject and makes this indicator the least empirical of all. This indicator focuses on the depletion of stocks, meaning the reduction of the naturally found resources, not regenerated through recycling or other activities. Furthermore, depletion is measured through economic data, particularly the price of a resource, which is a value that is affected by a myriad of factors, not only its actual depletion.

Abiotic depletion potential for fossil fuel resources
A measure of the depletion for non-renewable fossil fuel resources. Measured in MJ, that is the mega joules that the fossil fuel resource generated. It is more of a measure of how much energy was generated through fossil fuels, than a measure of how much depletion the burning of the fossil fuels caused, since it doesn't take into account the natural stocks of the fossil fuels.

5 Life Cycle Inventory

This section will explain the materials for which data was collected. It will explain what material the original design uses and how it uses it, then the functionally equivalent alternative materials will be presented and explained. A table outlining the EPDs which are used to define the environmental impacts are presented for each material category, the links for all EPDs can be found in Table 13 in Appendix B. It is worth noting that some products do not declare a lifetime, thus it is assumed that those products have a lifetime equal to the lifetime of the assessed building.

5.1 SIP sheathing

The original design uses LVL sheathing for the SIPs. LVL is an engineered wood created by gluing together multiple layers of veneer, thin wood slices, in the same direction. The LVL in the original design is of the same thickness throughout, 24 mm. For the alternative materials different thicknesses are assumed, so as to achieve structural equivalence through a simplified structural calculation, which was explained in chapter 4.2.3.1.

Three products were selected for creating an aggregated average for LVL. First, the LVL which the client used, *Kerto*. However, the EPD for *Kerto* didn't declare EoL modules, thus two other products were added to create a representative average, *StoraEnso* and *Steico*. *StoraEnso* declared an absurdly high estimate for ozone depletion potential for module D, thus only the more realistic estimate by *Steico* is used instead. The EoL scenario of incarnation proved to be the best-case scenario, however it is worth noting that the scenario of re-use doesn't incorporate that after re-use the LVL can be burned for energy recovery. Energy recovery following re-use is probably the best-case scenario, but this wasn't incorporated in this LCA.

For the alternative sheathing materials, the following was selected:

- Oriented strand board (OSB). An engineered wood, created by combining adhesives with flakes of wood. Specifically, the type OSB/3, as defined through EN 300, is selected, this type of OSB is load bearing and can be used in humid conditions. This is one of the most used materials for SIPs. *Medite Smartply* declared a very high value of abiotic depletion potential for non-fossil fuel resources for the product stage, this is unrealistic considering no rare minerals are used in the production of OSB. Thus, the abiotic depletion potential for non-fossil fuel resources results for the product stage of *Medite Smartply* OSB where ignored.
- Magnesium oxide boards (MgO). These boards are known for their supreme fire resistance, mold, and mildew control. They are usually used as wall and ceiling covering; however, they are also used in SIPs. They are often applauded for being environmentally friendly, but only relatively to other drywall products, such as gypsum and cement. The EPD found for MgO is not for structural application, thus another MgO product was used technical information relating to the E-modulus for the MgO. The main difference

between the MgO in the EPD and the MgO whose technical information was used is that the latter contains more layers of fibre glass reinforcement. Fibre glass only amounts to a small percentage of the total composition of the MgO boards, and according to EN 15978 if no specific EPD is available, an EPD for a similar product may be used.

- Fibre cement. Is a composite composed of cement reinforced with cellulose fibres. While its common use is for cladding and roofing, some companies produce SIPs with it, due to its strength and performance. Like MgO it is highly resistant to mold and fire, as well as being resistant to water.

In Table 3 the overview of all selected EPDs for the sheathing materials is given.

Table 3 Information of selected EPDs for sheathing (ND: Not Declared)

	Company	**Country**	**Database**	**Modules declared**	**Service life**	**EoL Scenarios**	**Avg density (kg/m3)**	**Moisture content**	**Stored carbon (kg CO2 eq)**	**Specific product**	**Modulus of elasticity (N/mm2)**	**Thermal conductivity (w/mk)**
LVL	Kerto	Finland	Ecoinvent 3.5	A1-A3	ND	ND	510	8-10%	789	Kerto Q-panel	8300	0.13
	StoraEnso	Finland	Gabi 2018	A1-D	Lifetime of building	Re-use, recycling, energy recovery, landfill	510	8-10%	804	LVL X	8800	0.13
	Steico	Germany	Gabi 2019	A1-A3 A5 C2 C3 D	Lifetime of building	Energy recovery	530	</= 12%	ND	LVL X	9000	0.13
OSB	EGGER	Austria	Gabi 2018	A1-A3 C3 D	50 years	Energy recovery	607	5%	ND	OSB 3	3500	0.13
	MediteSmartply	Ireland	Ecoinvent 3.4	A1-A3	ND	ND	600	2-12%	976	Smartply Max (OSB3)	3500	0.13
MgO	Tecbor	Spain	Ecoinvent 3.2	A1-A3 C2 C4 D	25 years	Landfill	925	ND	0	Tecbor Fireproof rigid boards	475	0.31
Fibre Cement	Wienerberger	Belgium	Ecoinvent 3.5	A1-D	60 years	Landfill	1700	ND	77	SVK Fibre cement flat sheets	14000	0.37

5.2 Insulation

The original design uses expanded polystyrene foam (EPS) for the insulation. This is arguably the most common type of insulation for SIPs. They are perfect for SIPs due to their rigidity, which serves as an interconnection between the outer layers of the SIP, the sheathing material. The EPS used in the original design has a high density, 35 kg/m^3. Only EPDs for lower densities where available, but they mostly followed a linear relationship, thus it was possible to estimate the environmental indicator scores for the high-density EPS.

The alternative material for the insulation is extruded polystyrene (XPS). XPS is composed of the same materials as EPS, polystyrene with small amounts of flame retardants and blowing agents, but the process of manufacturing differs. XPS is generally stronger and denser than EPS, however the original design already uses relatively dense EPS, the density of which is around the same as the densities of the XPS it is going to be compared to.

The other alternative material is polyurethane board (PUR). This is a common material for SIPs and is famous for having the lowest thermal conductivity of all insulation types. The specific EPD for this insulation type was selected to be with mineral fleece facing, as that is a good surface to use with adhesives.

Even though the rigid insulation boards fulfil a structural function, this is mostly as an interconnection between the "skins" of the SIPs. Otherwise, the three materials have no bending strength and a compressive strength of 250 for EPS, 200-450 for XPS and 150 for PUR. Given this, it is assumed that the same thickness of insulation is needed to achieve structural functional equivalence.

In Table 4 the overview of all selected EPDs for the insulation materials is given.

Table 4 Information of selected EPDs for insulation (ND: Not Declared)

	Company	**Country**	**Database**	**Modules declared**	**Service life**	**EoL scenarios**	**Avg density kg/m3**	**Thermal conductivity (w/mk)**	**Modulus of elasticity (N/mm2)**	**Thermal conductivity (w/mk)**	**Compressive strength**
EPS	Eumeps	Belgium	Gabi 2017	A1-A5 C2-D	Life time of building	Incineration, recycling	35	0.033	12	0.033	250
XPS	Exiba	Belgium	Gabi 2013	A1-A4 C2 C4 D	Life time of building	Landfill, incineration	35	0.0355	25	0.0355	425
	Danosa	Spain	Ecoinvent 3.2	A1-C4	50 years	Landfill	32.41	0.034	ND	0.034	200
PU	PU Europe	Belgium	Gabi 2013	A1-A5 C2-D	50 years	Energy recovery	31	0.026	ND	0.026	150

5.3 Adhesive

An adhesive is needed to assemble the SIPs, by gluing the sheathing to the inner core (the insulation). The layer of glue between a layer of skin and the core is around 0.125 mm. The EPD for the adhesive was selected to be reactive resin containing solvent, as solvent based adhesives are used for demanding and long-term application. It is assumed that 1% of glue is wasted during assembly, this is declared in module A5 while module D declares the energy credits for incinerating this waste.

In Table 5 the overview of the selected EPD for the glue is given.

Table 5 Information of selected EPD for glue

	Company	**Country**	**Database**	**Modules declared**	**Service life**	**EoL scenarios**
Glue	FEICA	Belgium	Gabi 2014	A1-A5 D	Dependent on many factors	For D, incineration of packaging & installations losses and recycling of metal container

5.4 Foundation

The house contains a foundation made up of L and H steel beams, as well as steel foundation screws, this is explained in chapter 4.2.2.2. The connections between the beams, as well as between the L beam and the house is not included in this LCA. To calculate the environmental indicators, EPDs of steel sections where used, while those EPDs are not for steel foundation screws, they are deemed to be representative for them.

In Table 6 the overview of the selected EPDs for steel beams is given.

Table 6 Information of selected EPDs for steel beams (ND: Not Declared)

	Company	Country	Database	Modules declared	Service life	EoL scenarios	Steel Grade
Steel beams	Duferco	Italy	Ecoinvent 3	A1-A4	ND	ND	S235 to S355
	Duferdofin	Italy	Ecoinvent 3	A1-A4	ND	ND	S235 to S355
	Bauforumstahl	Germany	Gabi	A1-A3 C3 D	ND	Mixed, recycling (88%) and re-use (11%) landfill (1%)	S235 to S960
	ArcelorMittal	Luxemburg	Gabi	A1-A3 C3 D	ND	Mixed, recycling (88%) and re-use (11%) landfill (1%)	ND

5.5 Glass and frame

The house contains two triple glazed windows, with a U value of 0.5. To achieve this with triple glazing, three 4mm thick panes are needed[1]. For the frame system, a standard aluminium window frame is selected, the U-value for this frame is in the range of 1.0-2.1W/m2K, the value selected for the energy use model is 1.39 W/m2k. The gap between the glass panes is assumed to be filled with air.

Kawneer's glass frame reported a very high abiotic depletion potential for non-fossil fuel resources for the product stage, around 600 times as much as of all other materials combined. Because this is unrealistically high, the abiotic depletion potential for non-fossil fuel resources for the glass frame is assumed to be 0. In Table 7 the overview for the selected EPDs for the glass and glass frame is given.

Table 7 Information of selected EPDs for glass and its frame (ND: Not Declared)

		Country	Database	Modules declared	Service life	EoL scenarios
Glass	Paniclear	Europe	Gabi	A1-D	30 years	Landfill
Glass frame	Kawneer	UK	Ecoinvent 3.2	A1-A3 C2 C4	ND	Recovery

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[1] According to Glass Technology Services

5.6 Roof membrane

The roof membrane is used to create a watertight covering to protect the building, it is installed on top of an angled EPS layer which is bounded by SIPs, this setup was explained in chapter 4.2.2.3. The original design uses *Leadax* roofing, which uses recycled PVB, from car glass, to create what they claim to be the "world's most sustainable flat roofing". Two alternative materials where selected to compare to *Leadax*, PVC and Bitumen, both being very commonly used materials for flat roofs. For bitumen many versions existed for the selected EPD, NTV1 is used since it's the simplest design.

Leadax reported a very high positive abiotic depletion potential for non-fossil fuel resources for module D, since the EoL scenario is recycling this doesn't make sense. Thus, the abiotic depletion potential for non-fossil fuel resources for module D for Leadax is assumed to be 0.

In Table 8 the overview for the selected EPDs for the roof membrane is given.

Table 8 Information of selected EPDs for roof membrane (ND: Not Declared)

Roof membrane	**Company**	**Country**	**Database**	**Modules declared**	**Service life**	**EoL scenarios**
PVB	Leadax	Netherlands	Ecoinvent 3.3	A1-B3 C1-D	ND	Recycling
PVC	Renolit	Spain	Ecoinvent 3.2	A1-A5 B4 C2-D	90 years	Mixed, 10% recycling, 45% incineration and 45% landfill
Bitumen	Danosa	Spain	Ecoinvent 3.4	A1-D	30 years	Mixed, 12% landfill, 82% recycling, 6% reuse

5.7 Wall membrane

The wall membrane protects the house from water in the same fashion the roof membrane does. High density polyethylene was selected as the material for this envelope, no alternatives where selected.

In Table 9 the overview for the selected EPD for the wall membrane is given.

Table 9 Information of selected EPD for wall membrane (ND: Not Declared)

	Company	**Country**	**Database**	**Modules declared**	**Service life**	**EoL scenarios**
Wall membrane	Du Pot	USA	Gabi 2016	A1-A5 C2 C4 D	ND	Landfill

5.8 Façade

The original design uses spruce wood cladding, the EPD used for this material is that of treated with ferrous sulphate. Many alternatives were chosen and are listed below:

- Basalt. A type of cladding made from melted basalt which is spun into fibres and pressed, producing a flexible and durable form of cladding
- Stone composite. Made from two thirds minerals obtained from bauxite with the rest being resin. This cladding has the aestheticism of the mineral, while combining the technical properties of the mineral and the polymers from the resin.
- Slate. This cladding is made completely of slate, which is cut into thin disks. This cladding is relatively expensive and heavy, weighting around 200 kg/m^2.
- Aluminium. This façade cladding is strong and lightweight, made from a zinc-aluminium alloy.
- Fibre cement. This cladding is essentially made from the same materials as the fibre cement product chosen for the sheathing. This cladding type is cheap, lightweight, and resistant to water, it also stores biogenic carbon since it contains cellulose.

In Table 10 the overview for the selected EPDs for the façade claddings is given.

Table 10 Information of selected EPDs for façade claddings (ND: Not Declared)

Façade	Company	Country	Database	Modules declared	Service life	EoL scenarios
Spruce Wood	Superwood	Norway	Ecoinvent 3.2	A1-D	60 years	Energy recovery
Basalt	Rockpanel	Netherlands	Ecoinvent 2.2	A1-A3 B2 C4	60 years	Landfill
Stone composite	Krion	Spain	Dap construccion & ELCD	A1-D	25 years	Landfill
Slate	Kivi	Finland	Ecoinvent 3.4	A1-A4 C1-D	ND	Mixed, recycling (50%) & re-use (50%)
Aluminium	Kalzip	Germany	Gabi 7.3	A1-A5 C2 C3 D	50 years	Re-use
Fibre cement	Equitone	Belgium	Ecoinvent 3.5	A1-D	50 years	Landfill

5.9 Plumbing

As explained in chapter 4.2.2.4, PB pipes are going to be used for the water supply, while PVC pipes are going to be used for the drainage of domestic wastewater. Whereas the EPDs for the PVC pipes give their declared units in kilograms, Tepfa's PB pipes are declared for a 100m^2 apartment. Thus, the results are obtained by multiplying the indicators given in Tepfa's EPD by 0.35, since the apartment of this study is 35 m^2.

In Table 11 the overview for the selected EPDs for the plumbing pipes is given.

Table 11 Information of selected EPDs for plumbing pipes (ND: Not Declared)

	Company	**Country**	**Database**	**Modules declared**	**Service life**	**EoL scenarios**
PB plumbing pipes	Tepfa	Belgium	Ecoinvent 2	A1-C4	50 years	Mixed
PVC plumbing pipes	Iplex	Australia	AusLCI	A1-A5 C1-D	100 years	Mixed, recycling (26.9%), landfill (73.1%)
	Vinidex	Australia	AusLCI & Ecoinvent 3	A1-A5 C1-D	100 years	Mixed, recycling (26.9%), landfill (73.1%)
	Rifteng	China	Ecoinvent 3	A1-A3	100 years	ND

6 Results

This chapter will present the results obtained through the life-cycle assessment modelling. First, the indicator scores for the original design will be explained. After that, the main changes for each alternative design are going to be discussed. The graphs for the indicators per life-cycle stage, and the table for the percentage difference between the original and alternative designs can be found in Appendix C .

Before going into the results, it is necessary to understand the following. First, transport was ignored in the presentation and discussion of results, since it had a negligible effect on the total, for all indicator scores. For reference, the biggest effect, as a percentage of the total impact, was for photochemical ozone creation potential for which it accounted for -0.0009%. These results are negative because of an assumption in GaBi, which is dubious since it implies that trucks clean the air from smog. Second, since this study compares alternatives to the façade cladding, roof membrane, insulation, and sheathing, the rest of the house's elements are going to be referred to as "the rest".

6.1 Original design

Global warming potential

The main contributor to the global warming potential is the heating and cooling of the house, responsible for 81% of the total. The embedded costs account for only 3%, mainly since the biogenic carbon stored in the wooden façade and LVL has a negative impact, which cancels out the global warming potential of the other materials. For the embedded costs, the insulation has a similar impact as the rest, while the impact of the Leadax roof membrane is a about a third of the impact of the insulation.

The end-of-life stage accounts for 16% of the total. Most of this impact, 73%, is due to the waste processing of the LVL, which includes the release of the stored biogenic carbon. The same is true for the wooden façade, which accounts for 17% of the total.

With the benefits beyond the life stage, module D, the global warming potential can be reduced by 12% of the total, primarily due to the energy recovery of the LVL and recycling of the EPS.

The total global warming potential for the original design is 5.17E+04 kg CO_2 eq. Figure 10 illustrates the results for this indicator.

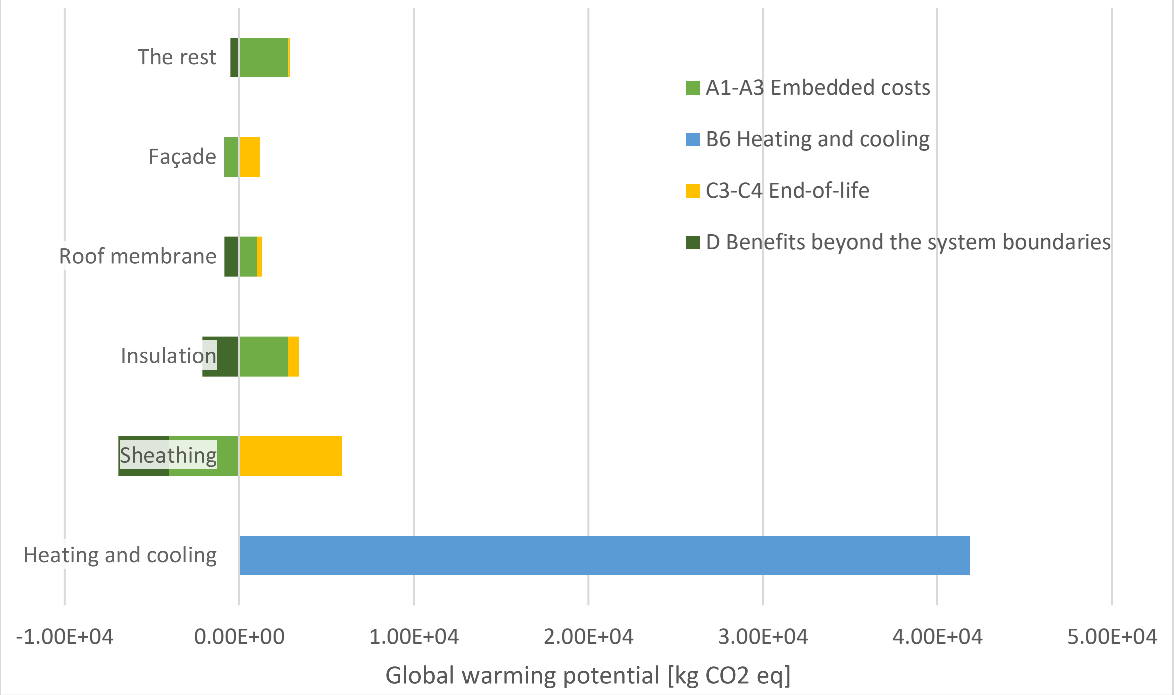

Figure 10 Global Warming Potential results for original design

Ozone Depletion Potential

The original design has an ozone depletion potential of 2.26E-04 kg CFC-11 eq, which can be reduced to 1.89E-04 if module D is accounted for. This is a small impact, for reference a typical refrigeration unit of 3 m^3, that you can commonly find in supermarkets, has an ozone depletion potential of 1.50E-02 for all of its life-cycle stages (Rossi, Favi, Germany, & Omicioli, 2021). Figure 11 illustrates the results for this indicator.

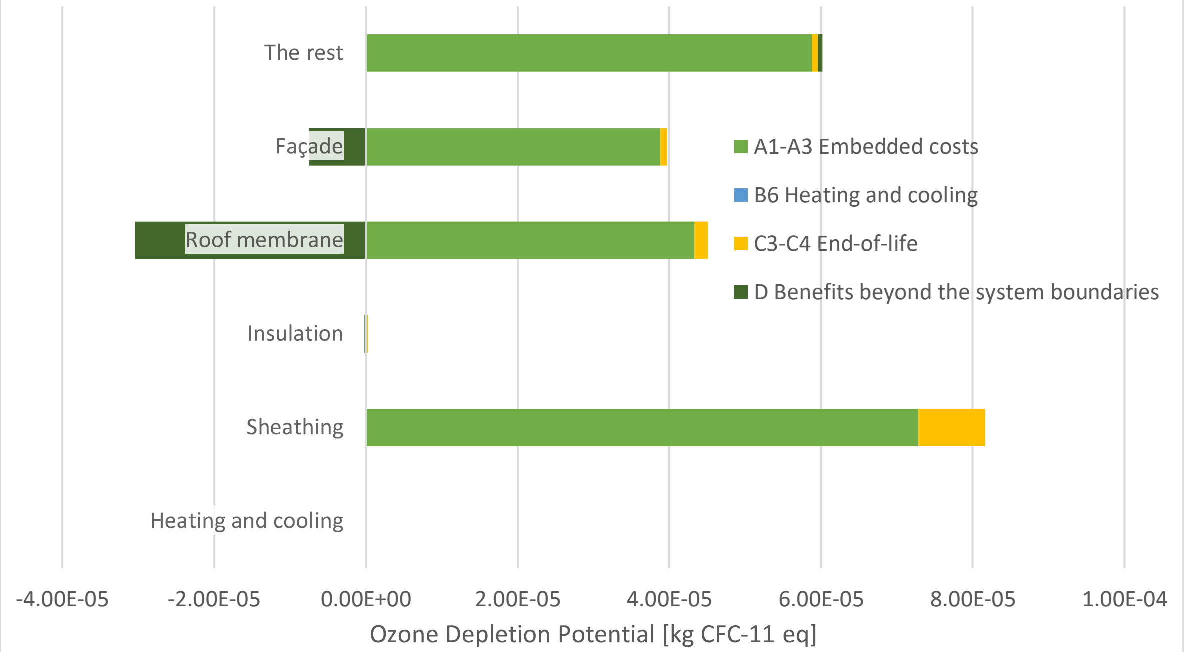

Figure 11 Ozone Depletion Potential results for original design

Acidification Potential

The total acidification potential equals 68.8 kg SO2 eq, with heating and cooling being responsible for half, while the embedded costs of the materials accounts for 47%. Most of the acidification potential for the materials is due to the electricity use in manufacturing. Accounting in module D, a reduction of 21% of the total can be achieved. Figure 12 illustrates the results for this indicator.

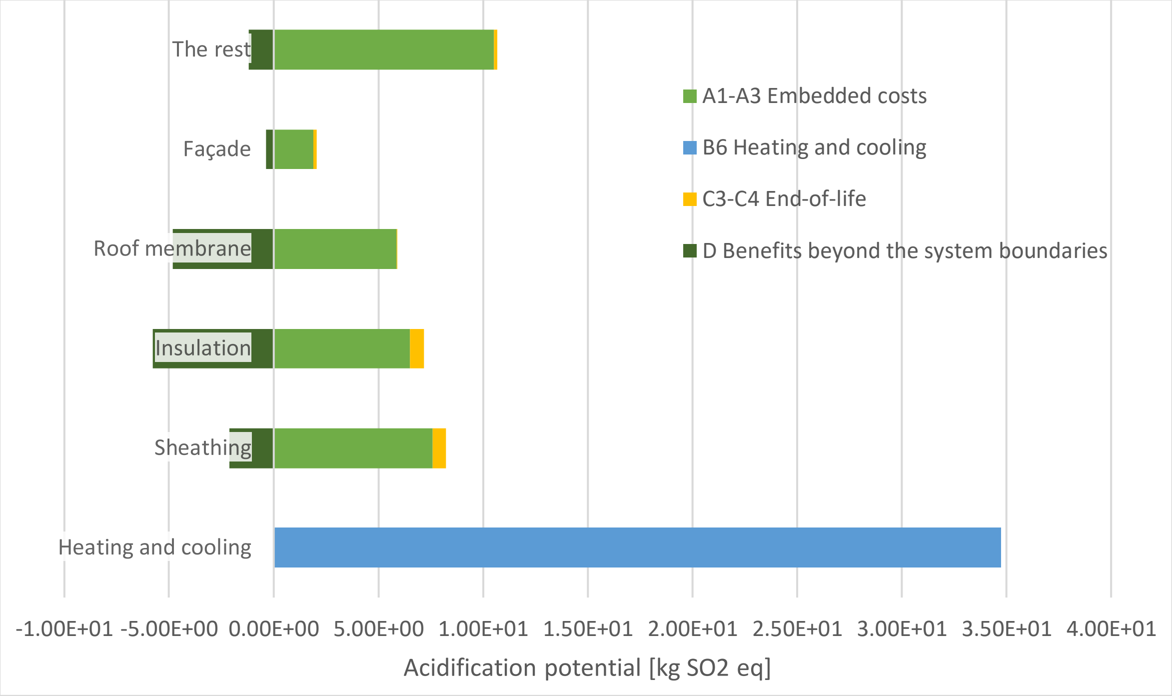

Figure 12 Acidification Potential results for original design

Eutrophication Potential

The total eutrophication potential for the original design is 13.2 kg [PO4]3 eq, with heating and cooling having 55% of the impact, while the embedded costs and EoL account for 40% and 5% respectively. Most of the eutrophication potential related to the materials is due to the electricity costs of manufacturing. With module D the total is reduced by 9%. Figure 13 illustrates the results for this indicator.

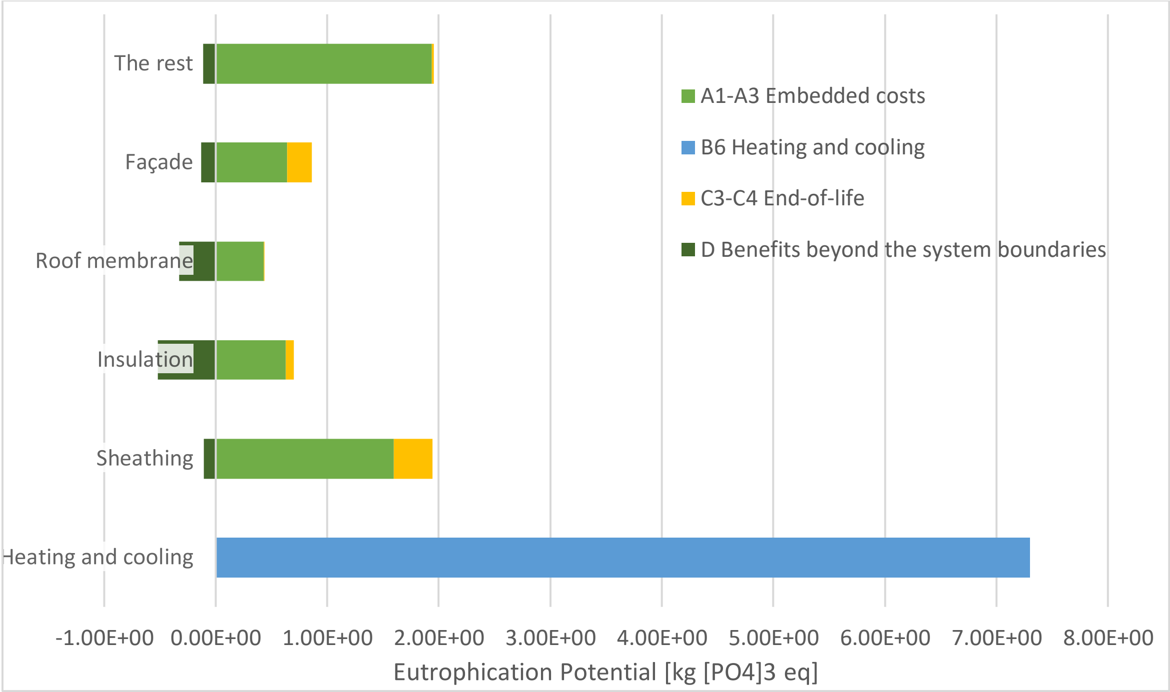

Figure 13 Eutrophication Potential results for original design

Photochemical Ozone Creation Potential

The total photochemical ozone creation potential is 1.94E+01 kg Ethene eq. The embedded costs of the EPS insulation is responsible for 59% of the total photochemical ozone creation potential, due to the use of pentane in the manufacturing process. A 10% reduction is achieved when implementing module D. Figure 14 illustrates the results for this indicator.

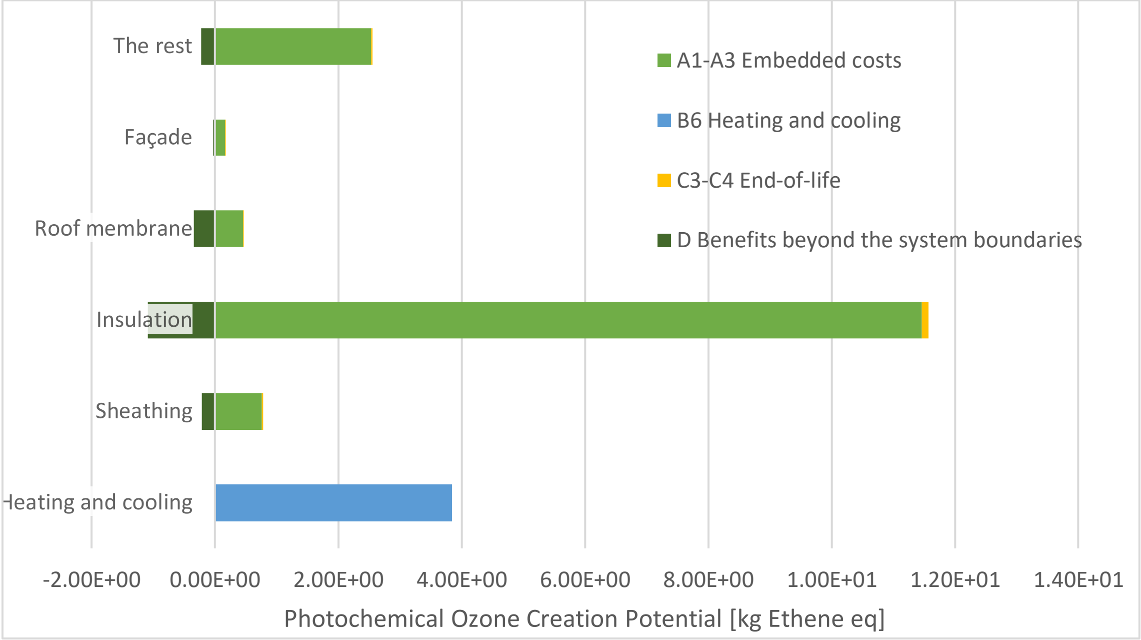

Figure 14 Photochemical Ozone Creation Potential results for original design

Abiotic Depletion Potential for non-fossil fuel resources

The total abiotic depletion potential for non-fossil fuel resources is 1.92E-02 kg Sb eq, this value might seem small, but its reference unit is based on antimony, a rare mineral that is at risk of depletion. For reference, 1 kg of aluminium equals to 1.09E-09 kg of antimony according to EN 15804 A1.

Heating and cooling accounts for 34% of the total, while the rest is largely due to the embedded costs of the materials. LVL sheathing accounts 19% of total, this is primarily due to the electricity cost of manufacturing and the use of adhesives.

When accounting for module D, a 13% reduction of the total abiotic depletion potential for non-fossil fuel resources is achieved. Figure 15 illustrates the results for this indicator.

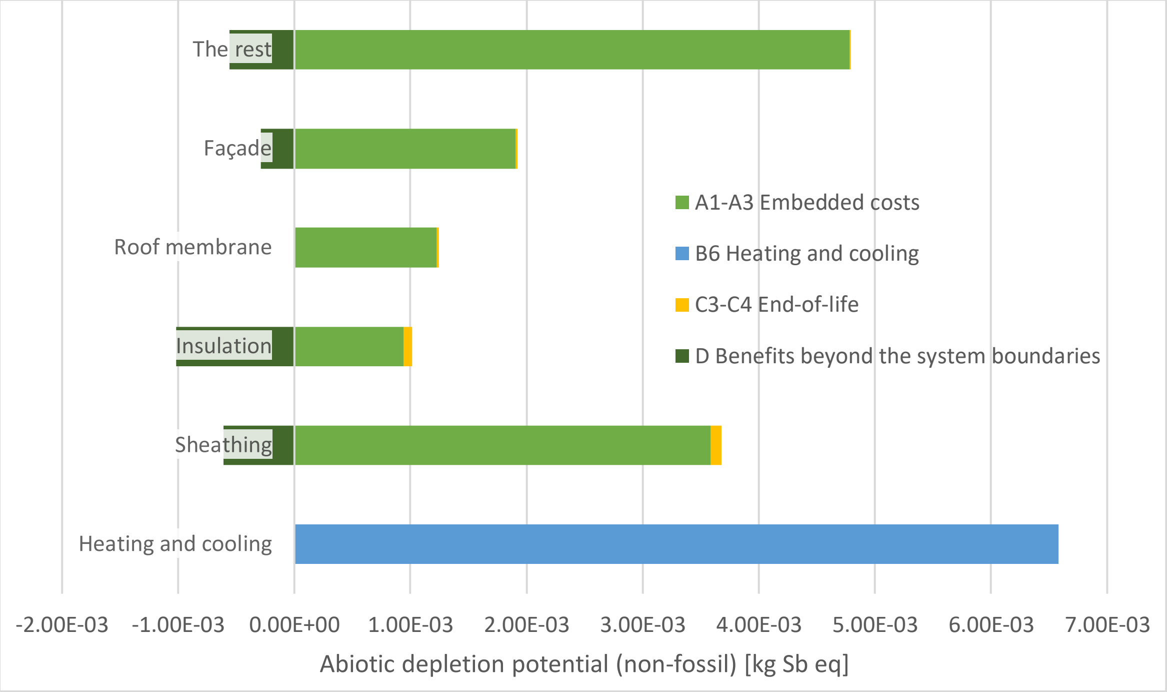

Figure 15 Abiotic Depletion Potential for non-fossil fuel resources results for original design

Abiotic Depletion Potential for fossil fuel resources

The total abiotic depletion potential for fossil fuel resources is of 6.78E+05 MJ, primarily due to energy cost of heating and cooling, since the Netherlands uses primarily natural gas and coal for energy production, as can be seen in Figure 8. The contribution of the materials is due to energy use in the manufacturing process. The Leadax roof membrane and the wooden façade have a relatively negligibly contribution since the companies use primarily renewable energy.

When accounting for module D, a 19% reduction of the total is achieved. Figure 16 illustrates the results for this indicator.

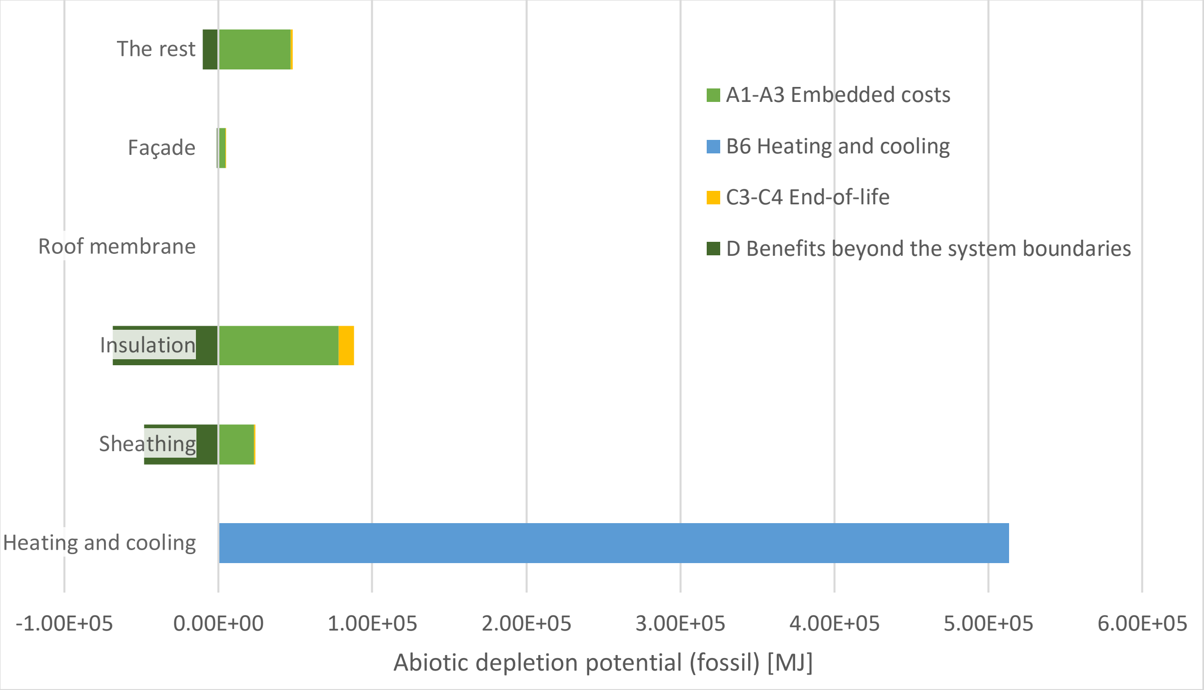

Figure 16 Abiotic Depletion Potential for Fossil fuel resources results for original design

6.2 Alternatives

In this section the results for the alternatives are going to be discussed per environmental indicator. Percentage increases are going to be mentioned a lot in this section, unless otherwise specified, the specified percentage increase is going to be including module D, the benefits beyond the system boundary.

Global warming potential

The original and OSB design scored very similarly, with only a small decrease for the original if considering D, since the thickness of the OSB sheathing is greater than the original's LVL thickness.

The MgO alternative design has a 15% increase, with module D, 8% without. This increase is mostly due to rise in the embedded costs, since MgO boards have no biogenic carbon storage. The same is true for the fibre cement sheathing, which have the greatest increase, 29%, due to having the costliest product stage of all designs.

For the insulations, the original's EPS scored very similar to XPS, with the only difference being a lower cost for EPS when including D. This is because the EoL scenario for EPS was recycling, whereas for XPS it was landfill. The biggest change was for PU, scoring the lowest for this indicator. This is because PU insulation had the smallest R-value, which makes the heating and cooling energy cost much lower than the other insulations.

For the façades, the most notable increase was a 11% increase, for composite stone. This is likely due to the energy intensive process of creating this product. Interestingly, the fibre cement façade scored similarly to the original's design, which uses a wooden façade. These results are intriguing since cement is clearly less environmentally friendly than wood, however this cladding is made up of approximately 32.5% cement, and contains 10% cellulose, which has biogenic carbon. The thickness of this cladding is 10 mm, whereas the wood cladding thickness is of 21 mm. Taking this into account, the similarity in the results between wood and fibre cement cladding could be because the energy costs of the wood processing and treatment are similar to the combined emissions due to the production of cement and the energy use of manufacturing fibre cement. Figure 17 illustrates the results.

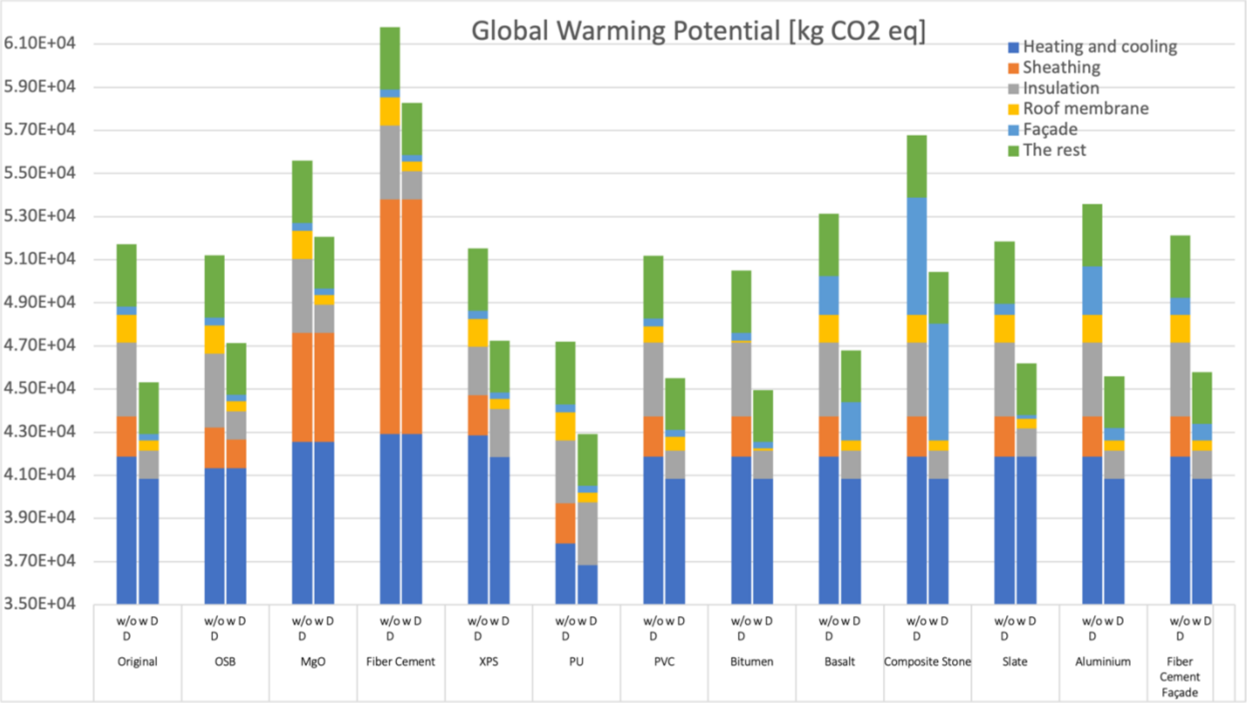

Figure 17 Results for Global Warming Potential

Ozone depletion potential

The fiber cement sheathing had a 425% increase, while the basalt façade cladding had a 513% increase. For the basalt this could be because of the use of the binder or the emissions in the melting of basalt rock. Whereas for the fibre cement, many ozone depleting gases are emitted in the production stage, such as nitrogen oxide, sulfur dioxide, and halon (Kin, Tae, & Chae, 2016).

The biggest increase was a tremendous 2463%, for the PU design. This is due to the production of PU involving the use of HCFCs refrigerants as a blowing agent, which, while much less potent than the previously use CFCs, still cause a noticeable impact if one is to look at the bigger picture. Figure 18 illustrates the results.

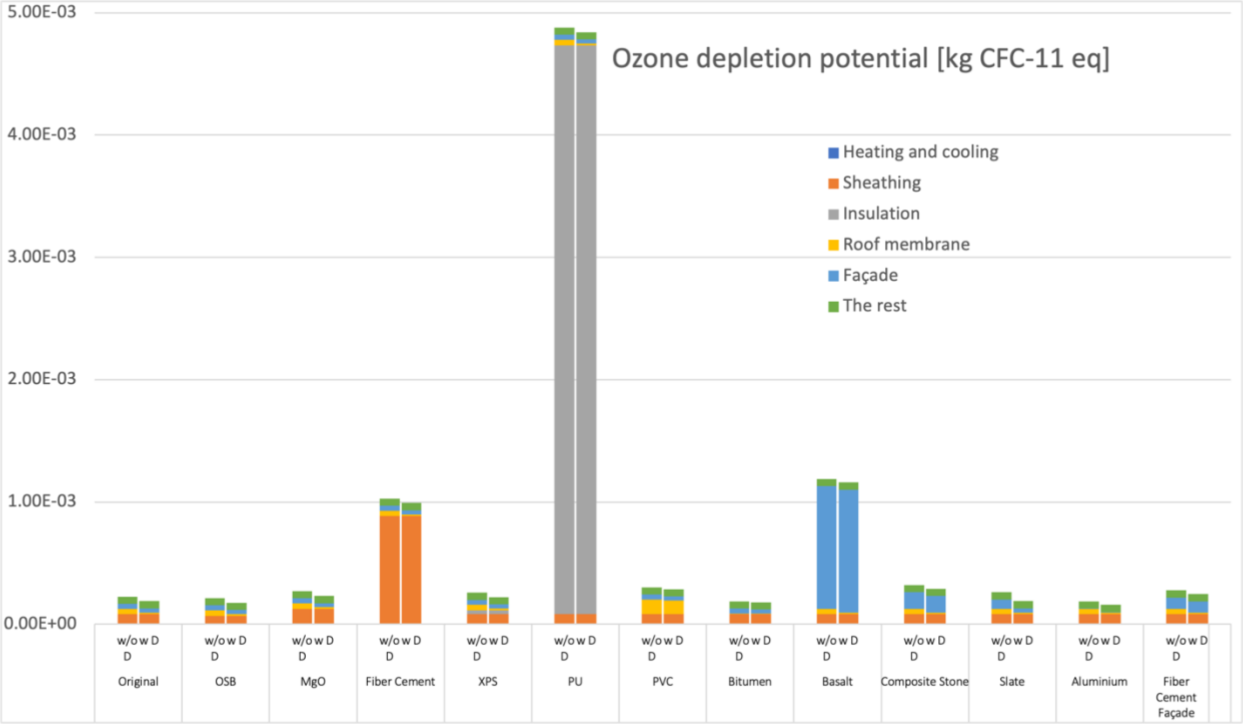

Figure 18 Results for Ozone Depletion Potential

Acidification potential

The fibre cement sheathing and composite stone façade had the biggest increase for this indicator, 59% and 49% respectively. MgO and XPS both had a smaller but relevant increase of 13%. Figure 19 illustrates the results.

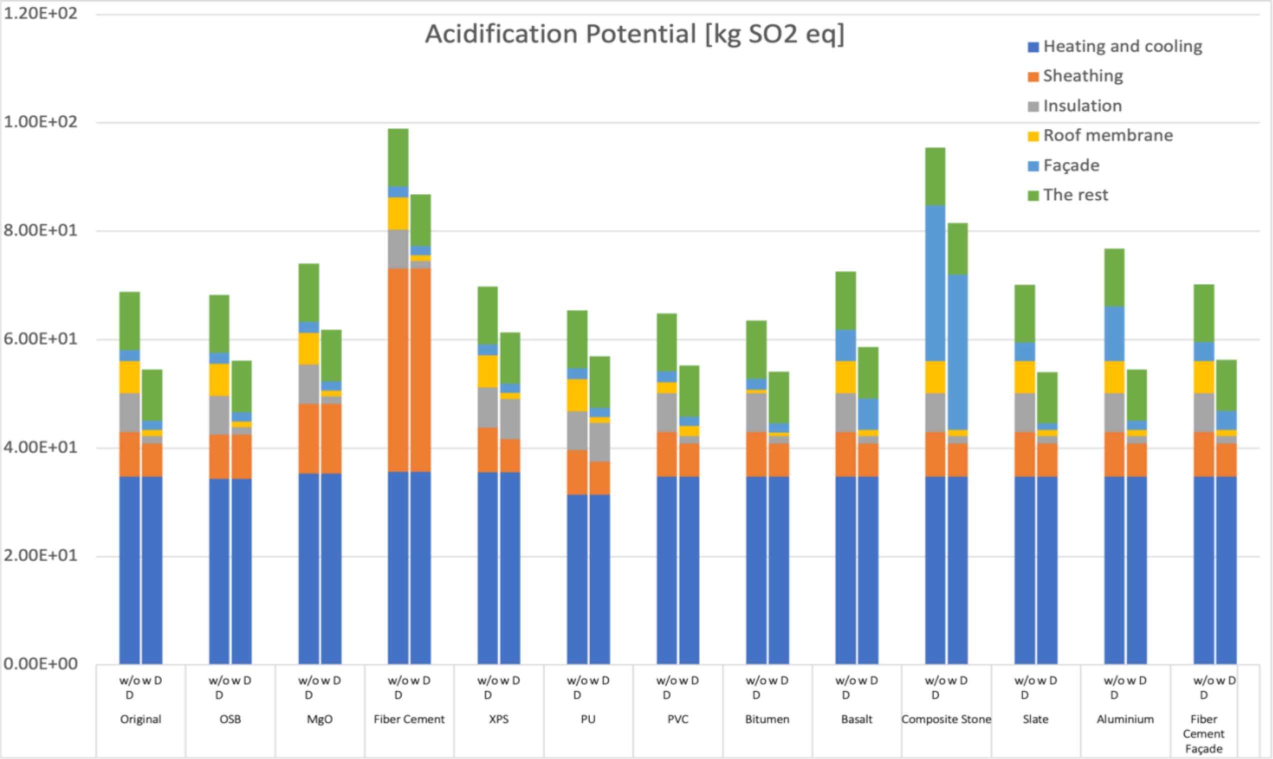

Figure 19 Results for Acidification Potential

Eutrophication potential

For this indicator, the increase was the highest for composite stone, 34%. This was followed by fibre cement sheathing, 30%, XPS, 27%, and MgO, 26%. Figure 20 illustrates the results.

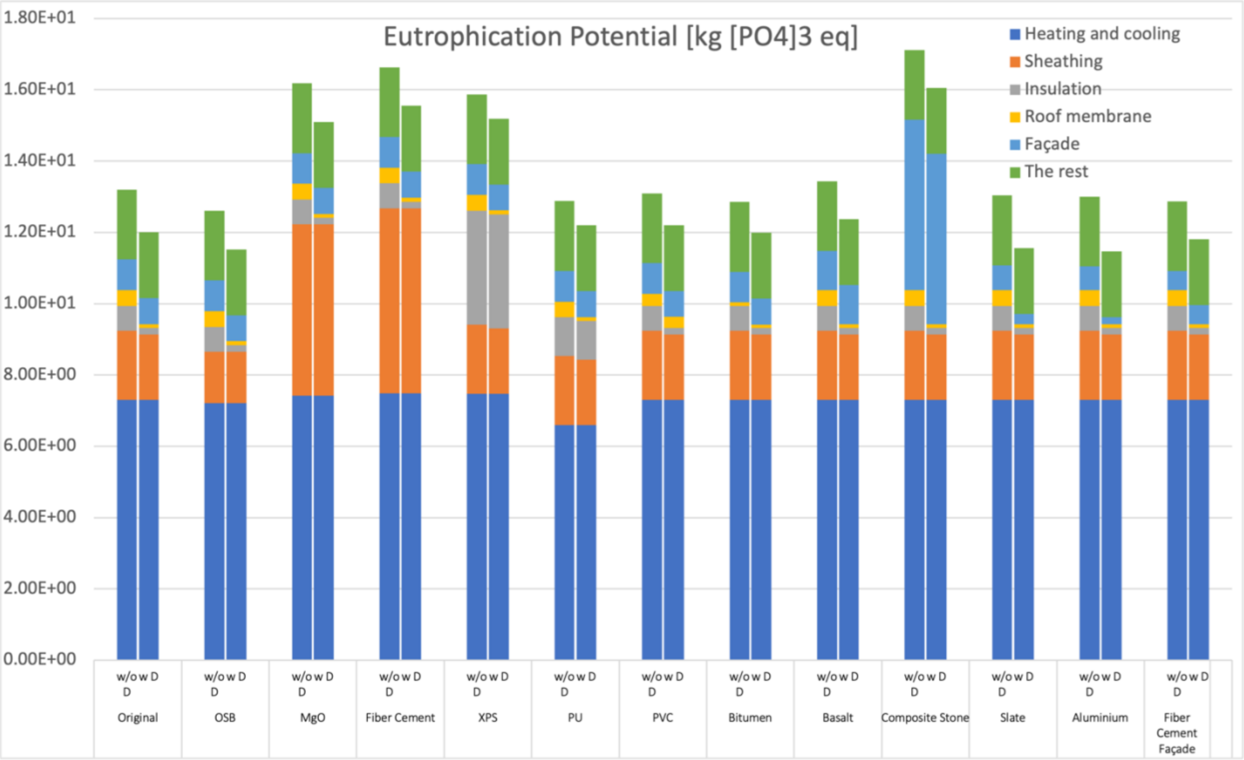

Figure 20 Results for Eutrophication Potential

Photochemical ozone creation potential

The only relevant increases for this indicator where for OSB and fibre cement, 10% and 13% respectively. However, the most relevant change are the decreases for the alternative insulation designs. XPS and PU achieved a 41% and 44% decrease, respectively. This is due to the use of pentane, as a blowing agent, in the production of EPS, which is used in the original design, where it is responsible for 59% of the total photochemical ozone creation potential. However, XPS can also use pentane, but the EPDs selected for XPS had either no pentane used, for *Danosa*, or pentane only formed a minor fraction of the blowing agent, for *Exiba*. For PU, pentane is also used, but only forms a small fraction of the total blowing agent, which, for this case, is mostly HCFCs. Figure 21 illustrates the results.

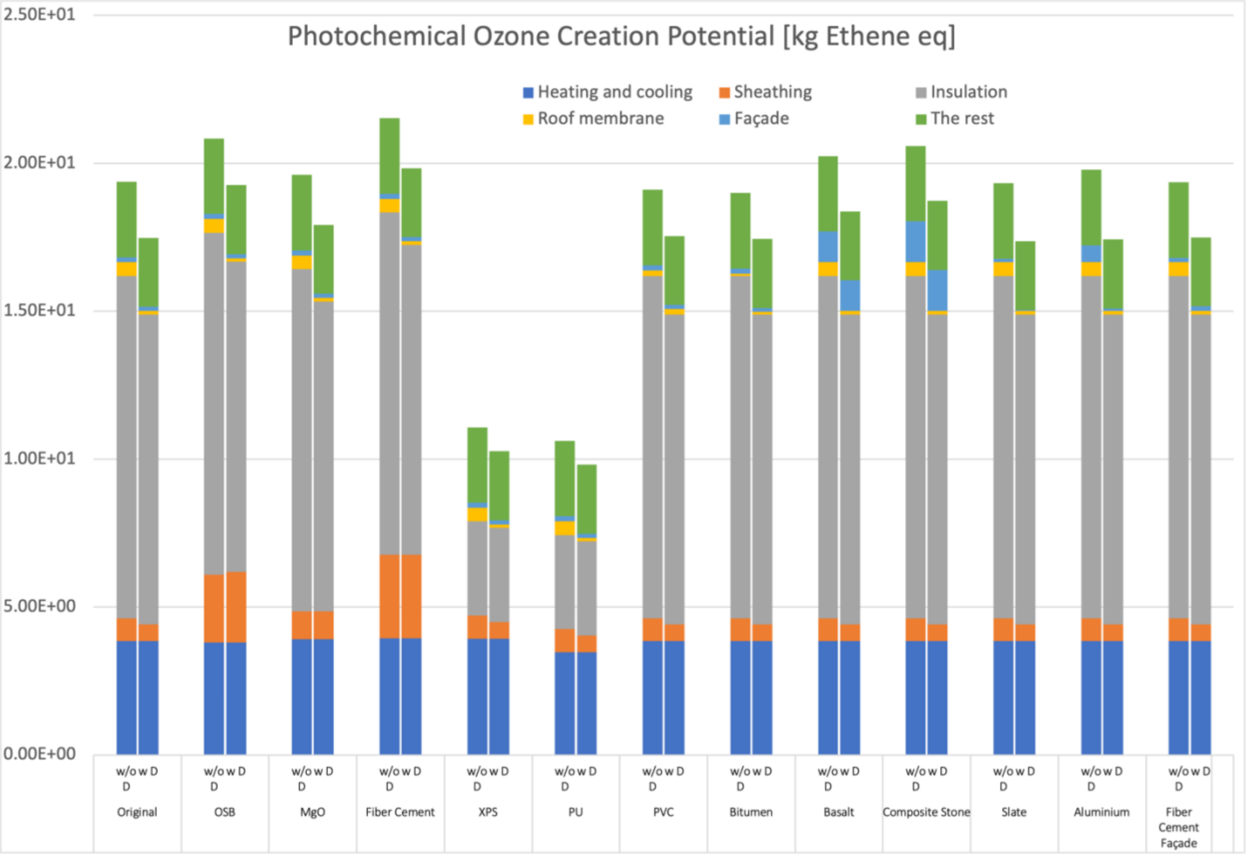

Figure 21 Results for Photochemical Ozone Creation Potential

Abiotic depletion potential for non-fossil resources

Two designs stand out for this indicator, fiber cement and aluminium, which have an increase of 250% and 437% respectively. For fibre cement, this is due to the presence of metal such as nickel and zinc in the cement. Whereas for the aluminium façade cladding, its due to it mainly being composed of aluminium, which a non-renewable material. The PU design has a 38% increase, due to the calcium carbonate in the PU board facing.

The OSB design has an odd 15% decrease for this indicator. Considering LVL and OSB use the similar amount of adhesive materials, and the OSB design uses more total volume of sheathing, this difference might be due to the dissimilarity in electricity use, e.g. OSB using more biofuel while LVL relies more on the electricity grid. Figure 22 illustrates the results.

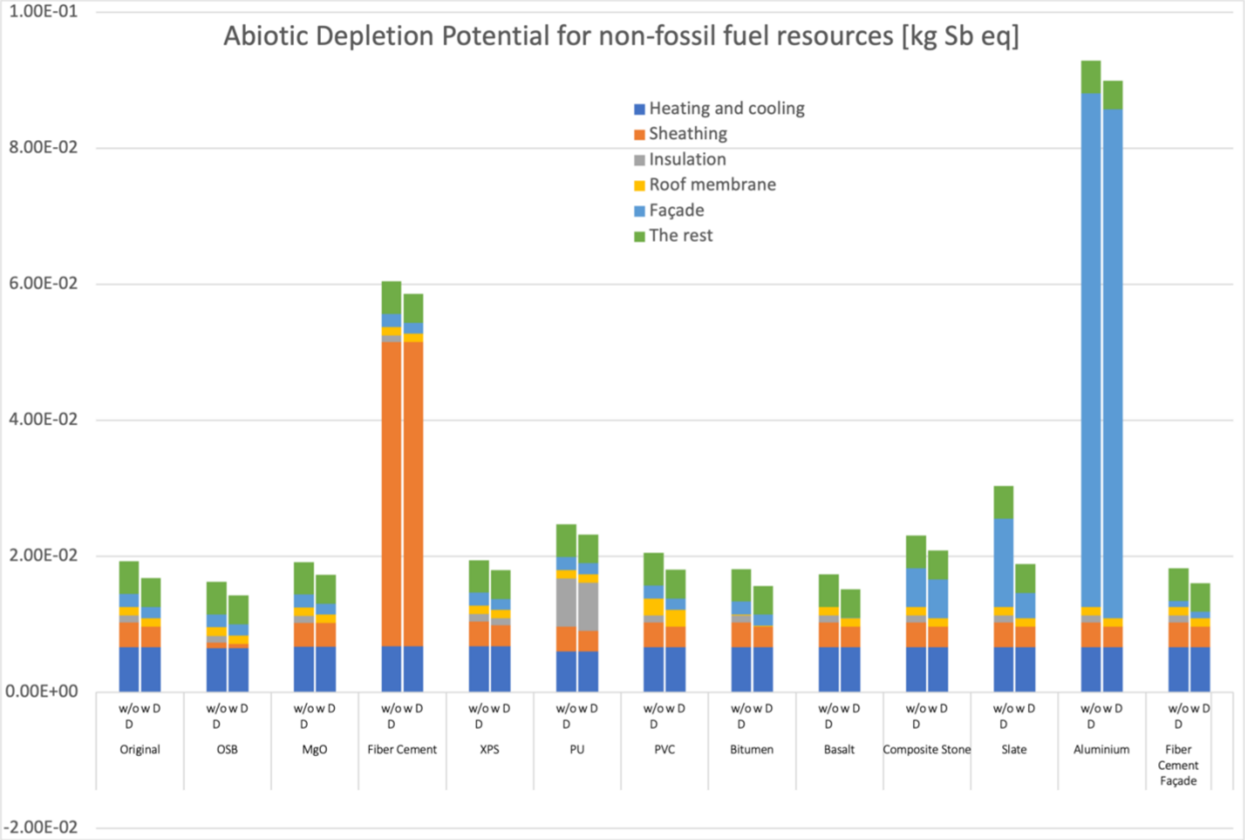

Figure 22 Results for Abiotic Depletion Potential for non-fossil fuel resources

Abiotic depletion potential for fossil fuel resources

The highest increase was for fiber cement, 29%, followed by composite stone, 15%, and MgO, 11%. These increases are due to a combination of more energy being required to make these products. The higher R-value for MgO and fibre cement, meaning more energy is used to heat up the house. And the EoL scenario, where MgO and fibre cement ends up in a landfill, whereas the LVL is used in energy recovery, where it replaces fossil fuels. Figure 23 illustrates the results.

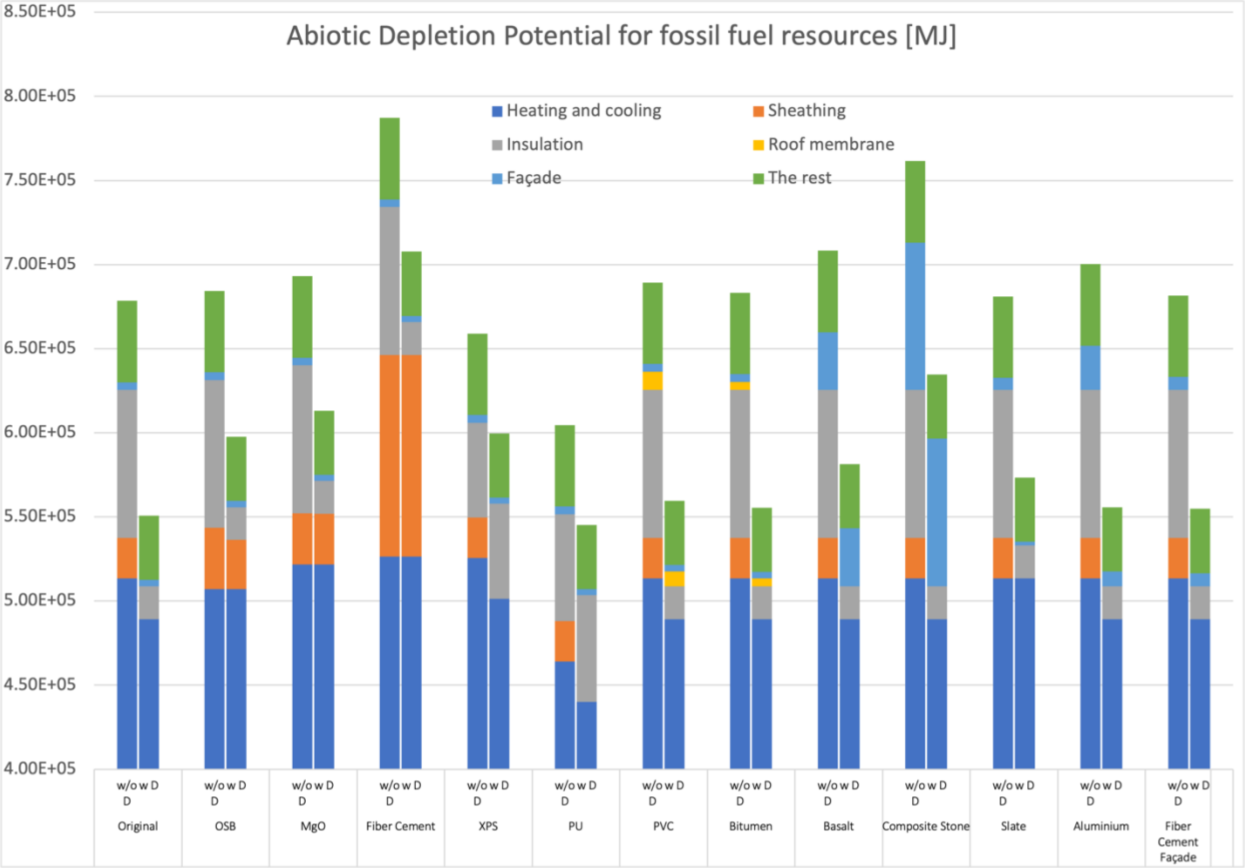

Figure 23 Results for Abiotic Depletion Potential for fossil fuel resources

7 Interpretation

In this chapter a discussion will be elaborated for each category of alternatives, that is for sheathing, insulation, roof membrane, and façade. Heating and cooling will also be discussed, as it has a very high contribution to most impact indicators. The discussion will interpret the results, pin-pointing the most important findings, and outline recommendations.

7.1 Sheathing

For the sheathing material, LVL and OSB clearly score the best for all indicators. Unsurprisingly, fibre cement scored the highest for all indicators, while MgO was in the middle. However, MgO boards have the highest fire resistance rating that is possible to obtain, relative to this LVL and OSB are quiet flammable. Considering this, the worse environmental score for MgO could be justified due to the added fire safety benefits. A recommendation is to consider making a hybrid SIP, where the inner sheathing is MgO, whereas the outside is LVL or OSB. Also, when considering cost along with environmental factors, the similar indicator scores for OSB and LVL makes OSB a better choice, since OSB is generally cheaper than LVL.

7.2 Insulation

EPS scored the best in most indicators, the big exception is for photochemical ozone creation potential, since the primary blowing agent for EPS is pentane, which has a big impact on this indicator. In the other hand, XPS uses CO2 and halogen-free co-blowing agents in the production process.

As for the PU included in this study, it used considerable amount of halogen blowing agents, which resulted in a big impact for ozone depletion potential. However, PU can be manufactured without using halogens, in fact using a combination of cyclopentane and water causes thermal conductivity values of 0.0214 W/mk (Choe, Lee, Seo, & Kim, 2004), which is lower than the value of the PU included in this study, 0.026 W/mk.

Insulation plays a crucial role in reducing energy use for heating and cooling, which is the life cycle stage with the most impact for global warming potential, acidification potential, eutrophication potential, and abiotic depletion potential for fossil fuel resources. The increased embedded costs of using more materials to build a house with thicker insulations are very much worth it because of the reduction of costs for heating and cooling.

7.3 Roof membrane

All three designs have very similar scores, except for the increased ozone depletion potential for PVC, which is something that can be ignored since the total ozone depletion potential in the PVC design remains very small. Thus, the claims *Leadax* makes about their PVB roofing being the most sustainable flat roofing product can be taken with a grain of salt. However, *Leadax* does fully use recycled PVB for their product, so if circularity is considered along with the indicators this roofing material does seem like the most environmental choice. But it is worth noting that the chosen bitumen roofing product uses a considerable amount of recycled materials, which could potentially be higher. As for PVC roofing, it could be made fully from recycled material, since PVC is fully recyclable. This discussion illustrates the importance of selecting products which are demonstrably made largely with recycled materials, when making environmental decisions in the building design process.

7.4 Façade

Overall, the original's design wooden façade had a mostly similar score to slate and fibre cement. Whereas the composite stone cladding product scores much worse for all indicators, while basalt and aluminium have a tremendous increase for ozone depletion potential and abiotic depletion potential for non-fossil fuel resources respectively.

Other things must be considered along environmental factors to decide what façade type fits best a particular design, such as moisture resistance, fire resistance, affordability, and weight. Slate is notoriously expensive and relatively heavy, whereas fibre cement is cheap and lightweight. Also, fibre cement has better fire, mold, and moisture resistance than wooden cladding.

7.5 Heating and cooling

Heating and cooling was the life cycle stage with the most impact for global warming potential, 81%, acidification potential, 50%, eutrophication potential, 55%, and abiotic depletion potential for fossil fuel resources, 76%. This is because the energy used for this life cycle stage came mostly from gas and coal. There are a few big takeaways from this. Firstly, the importance of the transition from fossil fuels to renewable energies cannot be emphasised enough, a bigger fraction of the energy grid coming from renewables will cause less environmental impact on all life cycle stage, since energy use is a part of all of them, excluding transportation. Secondly, insulation plays a crucial role as it reduces heat loss, reducing the amount of energy needed to heat or cool the house. Using PU, which has a better thermal conductivity than EPS, instead of EPS caused a 10% decrease in the total energy used for the 25-year lifetime. House designers should consider using thicker insulation, as the rise in embedded costs for extra materials will be compensated by the decrease in energy for heating and cooling. Thirdly, housing developers should seek to incorporate passive heating and cooling designs, as well as technologies such as heat pumps to further reduce the energy use throughout the lifetime of the building. Lastly, urban planners should seek to densify urban environments, to make apartments and multifamily houses instead of detached single-family houses. This not only reduces the amount of land and materials used per household, but also reduces the energy used per household. In fact, a household in an apartment building containing five or more units uses about half energy as single family homes, in the US (U.S. Energy information Administration, 2013).

8 Conclusion

This thesis project's goal was to conduct a comparative life cycle assessment for a modular tiny house, through the comparison of environmental indicators obtained from LCA analysis, for the original and alternative designs. Each alternative design changed one product from the original design, which resulted in 12 alternative solutions for the design. Only the products for the sheathing, insulation, roof membrane, and façade cladding were changed for the alternative designs. Using EPDs and the specifications of the house, as well as the energy model, it was possible to create a life-cycle model to generate results for all designs. The obtained results show that for the sheathing material, OSB and LVL scored the best for all environmental indicators, while fibre cement scored the worst. For the insulation EPS scored the best in all indicators but photochemical ozone creation potential. For the roof membrane, all three solutions had similar indicator scores, apart from the increased ozone depletion potential for PVC. For the façade, the wood, slate, and fibre cement scored similarly for all indicators, while composite stone scored the worst.

The main input for this project, apart from the specification of the house, were the indicator results from EPDs, which are freely available documents. The usage of EPDs for making ecological decisions in the design process of buildings, presents a free alternative to using expensive LCA software and databases. This is especially relevant for small companies, as well as companies in developing countries.

Overall, and considering the hiccups due to the cessation of work for the client, this project achieved its most important goal, to compare different designs solutions for the modular tiny house. However, the goal to include a more comprehensive LCA model for the whole building, meaning an LCA that includes more stages in its boundaries, and the goal of creating an LCA tool for the client was not performed.

9 Appendix A

Table 12 Quantification of used materials/products

	Volume (m3)	Area (m2)	Weight (tons)	Length (m)
SHEATHING				
LVL	6.592128	274.672		
OSB	9.064176	274.672		
MgO	8.24016	274.672		
Fibre cement	5.768112	274.672		
Insulation	25.47504			
Glue	0.034334			
H-beams			0.416296	
L beams			0.1677428	
Foundation screws			0.288	
Steel total			**0.8720388**	
Windows		22.122		
Window frame				16.898
Roof membrane		40.5107976		
EPS roof		6.9335772		
Wall membrane		79.681216		
Façade cladding		79.681216		
PVC un-pressurize pipes			0.032945	

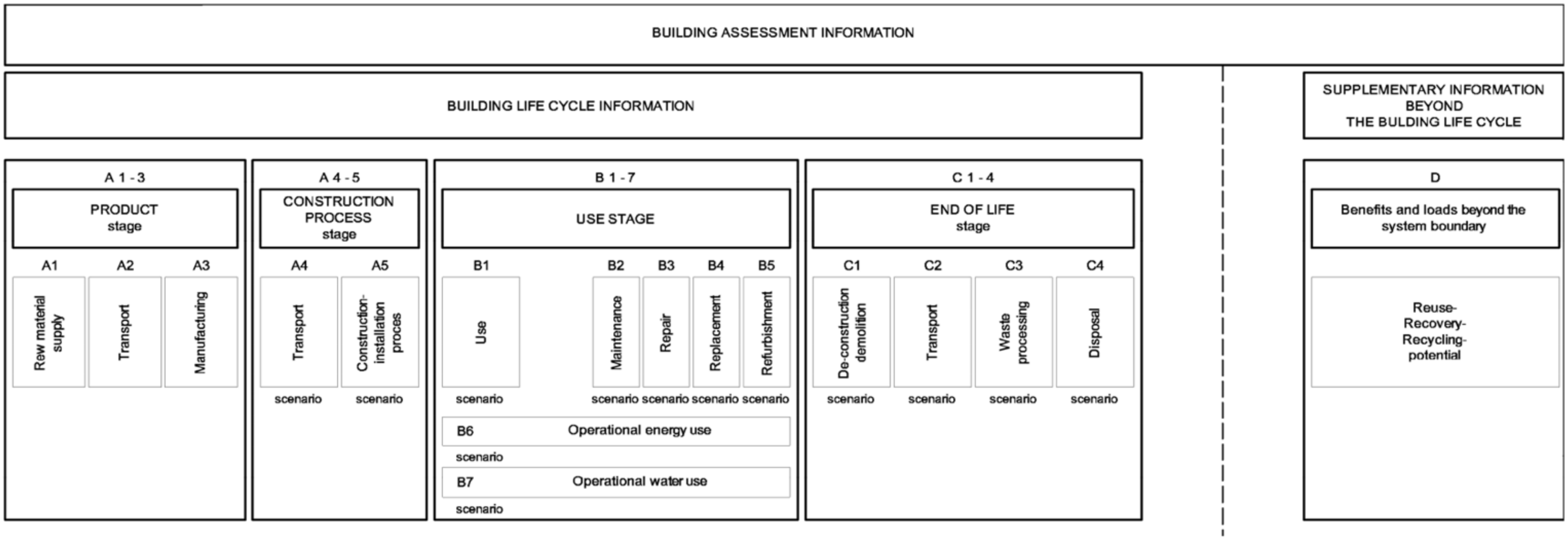

Figure 24 Life-cycle stages for building assessment

10 Appendix B

Table 13 Links to all EPDs used in this study

Sheathing	**LVL**	Kerto	Link
		StoraEnso	Link
		Steico	Link
	OSB	EGGER	Link
		MediteSmartply	Link
	MgO	Tecbor	Link
	Fibre Cement	Wienerberger	Link
Insulation	**EPS**	Eumeps	Link
	XPS	Exiba	Link
		Danosa	Link
	PU	PU Europe	Link
Glue		FEICA	Link
Steel Beams		Duferco	Link
		Duferdofin	Link
		Bauforumstahl	Link
		ArcelorMittal	Link
Glass		Paniclear	Link
Glass Frame		Kawneer	Link
Roof Membrane	**PVB**	Leadax	Link
	PVC	Renolit	Link
	Bitumen	Danosa	Link
Façade	**Spruce Wood**	Superwood	Link
	Basalt	Rockpanel	Link
	Stone composite	Krion	Link
	Slate	Kivi	Link
	Aluminium	Kalzip	Link
	Fibre cement	Equitone	Link
Plumbing	**PVB**	Tepfa	Link
	PVC	Iplex	Link
		Vinidex	Link
		Rifteng	Link
Wall membrane		Du Pont	Link

11 Appendix C

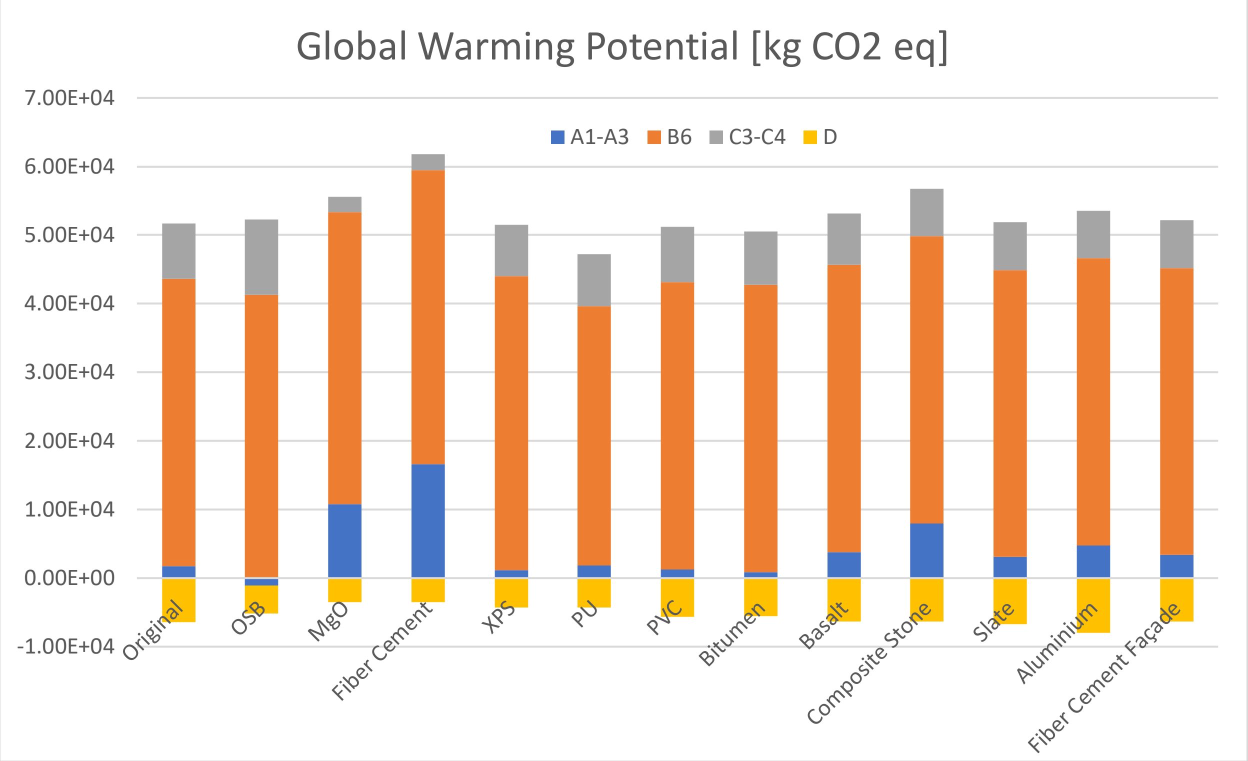

Figure 25 Results per life-cycle stage for global warming potential

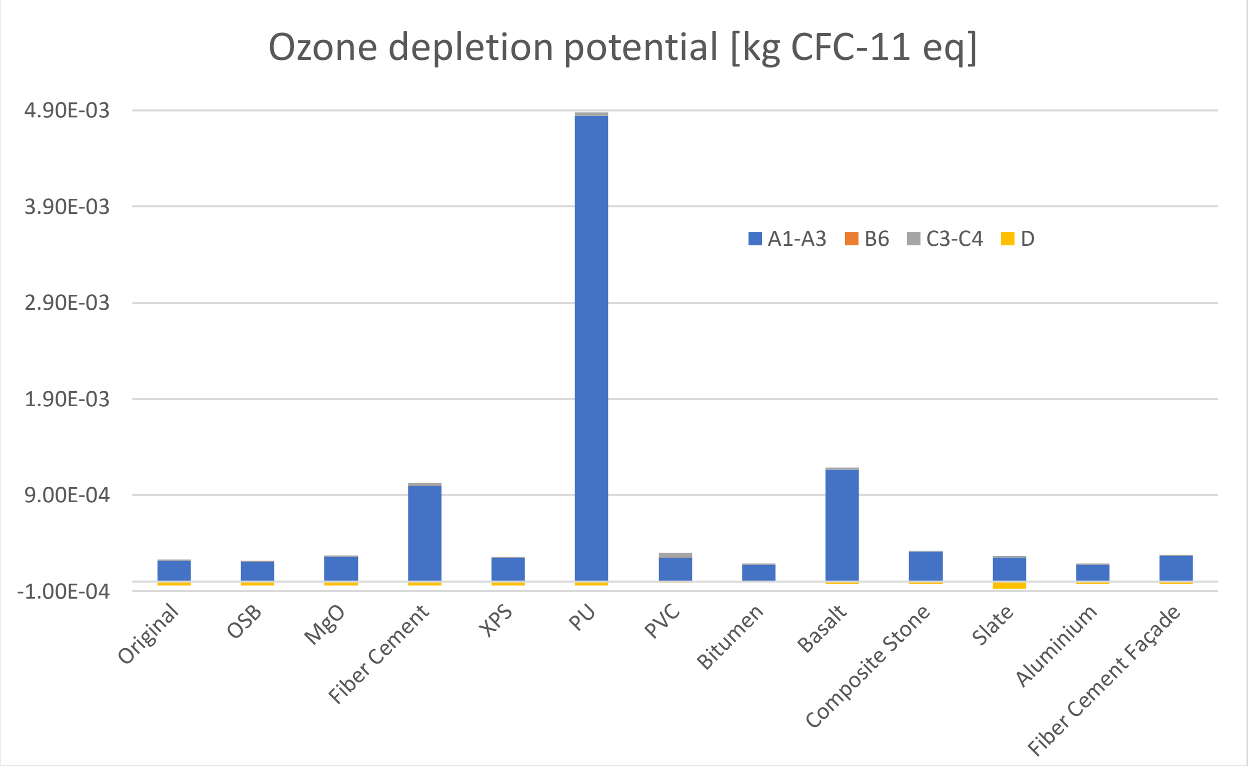

Figure 26 Results per life-cycle stage for ozone depletion potential

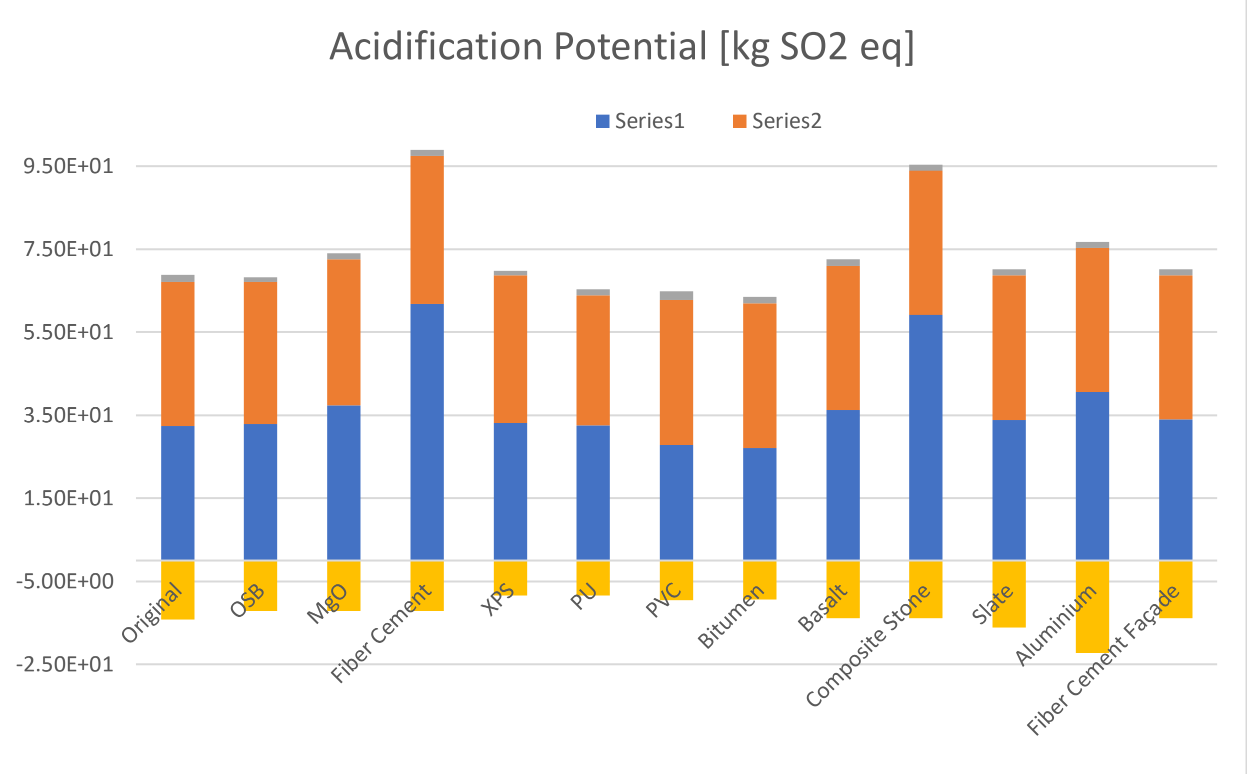

Figure 27 Results per life-cycle stage for acidification potential

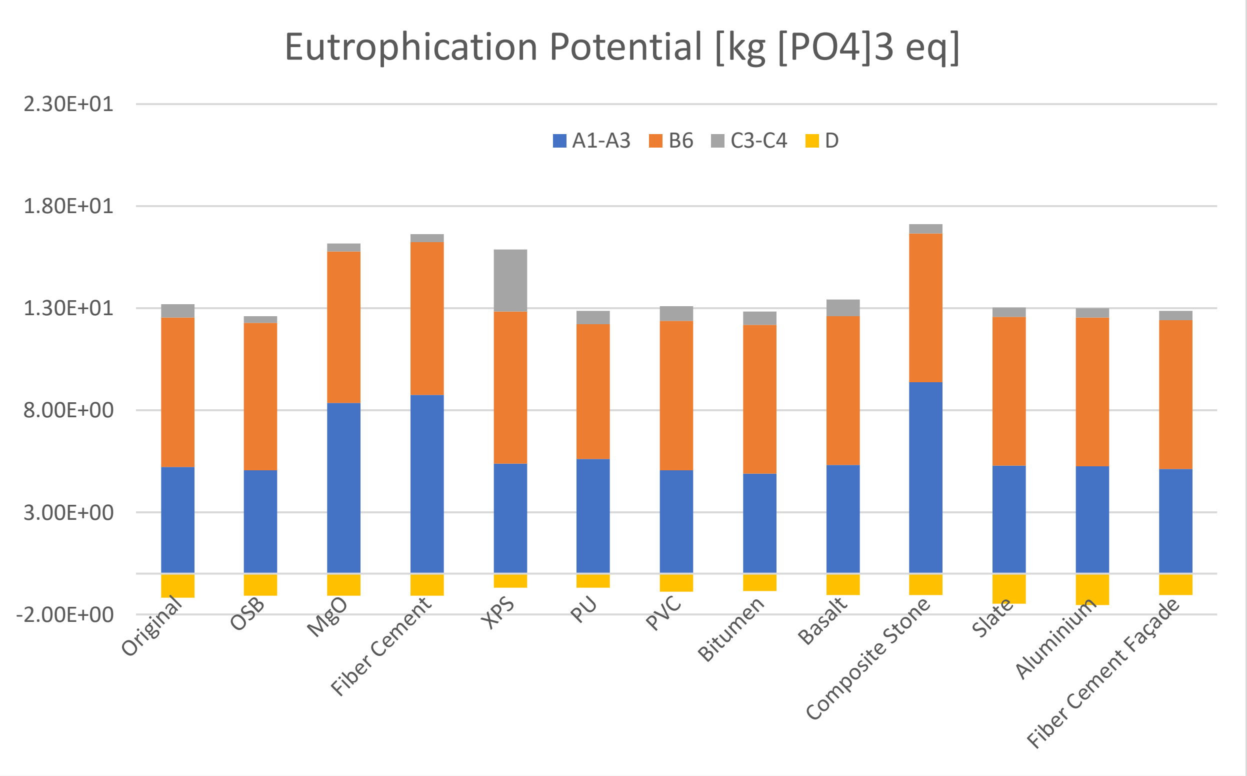

Figure 28 Results per life-cycle stage for eutrophication potential

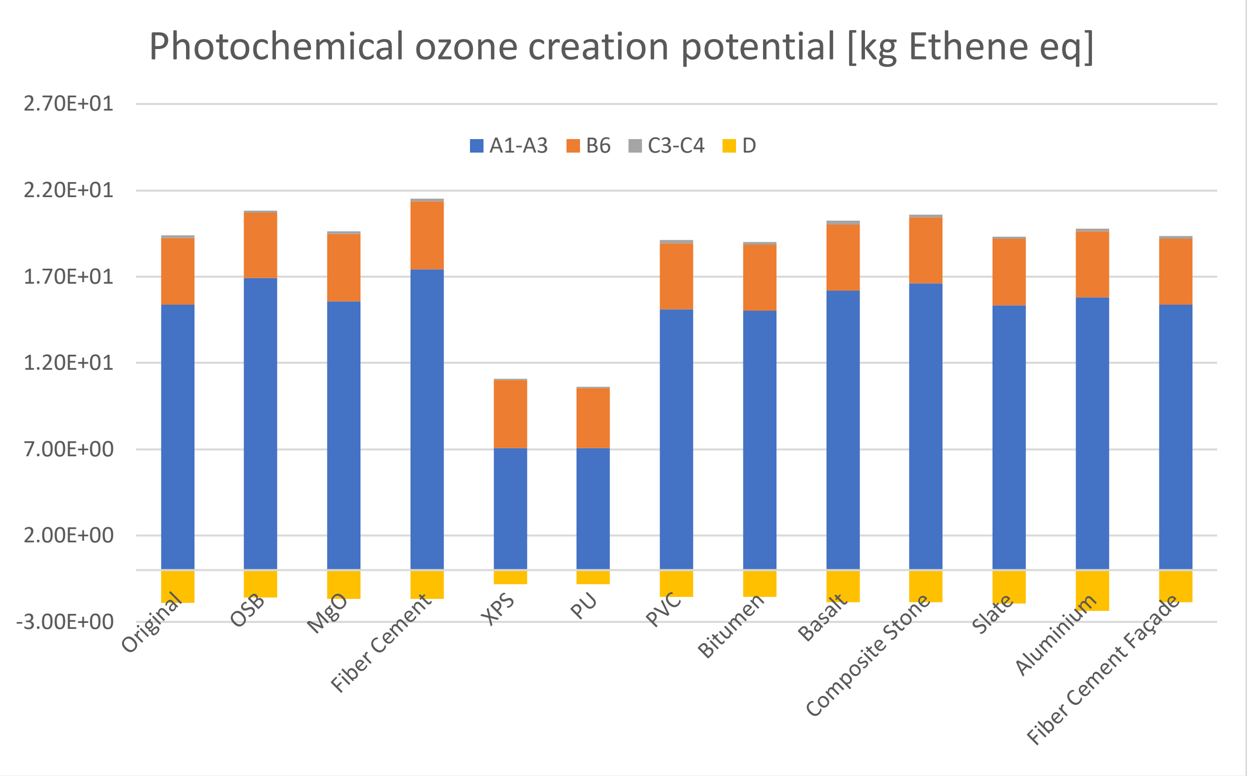

Figure 29 Results per life-cycle stage for photochemical ozone creation potential

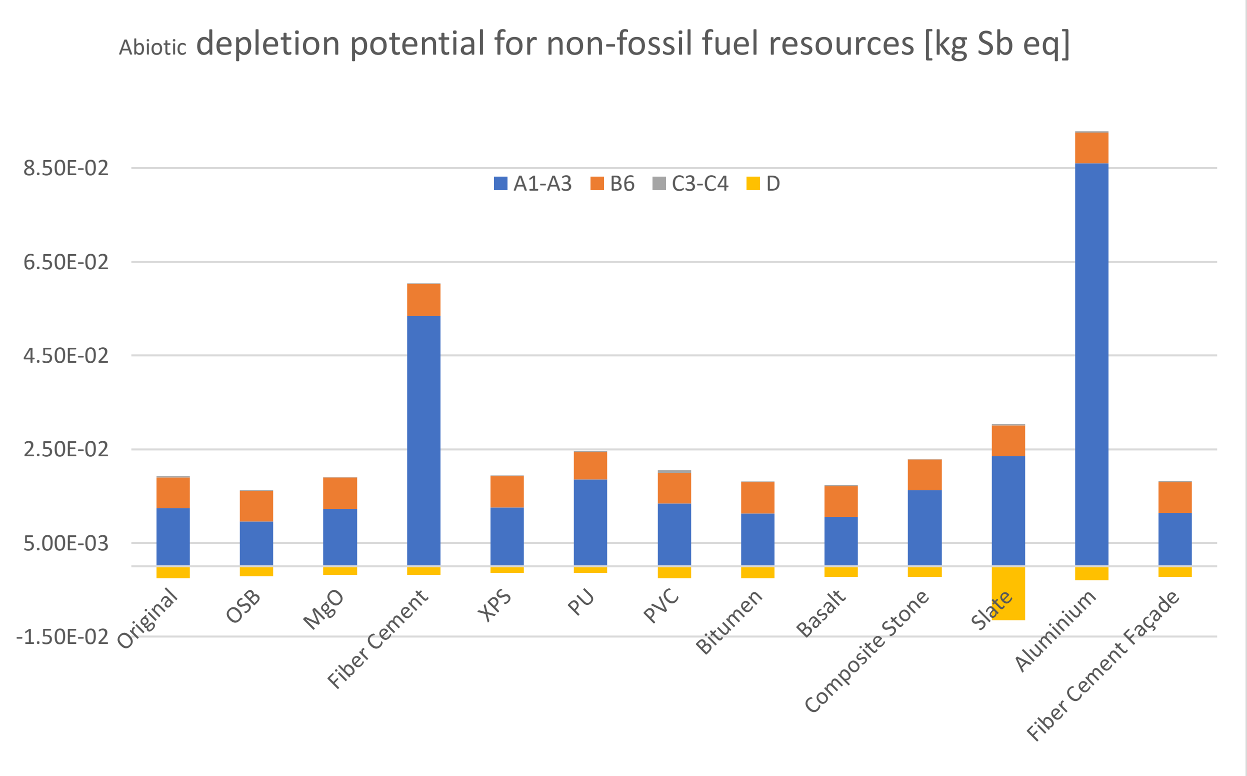

Figure 30 Results per life-cycle stage for abiotic depletion potential for non-fossil fuel resources

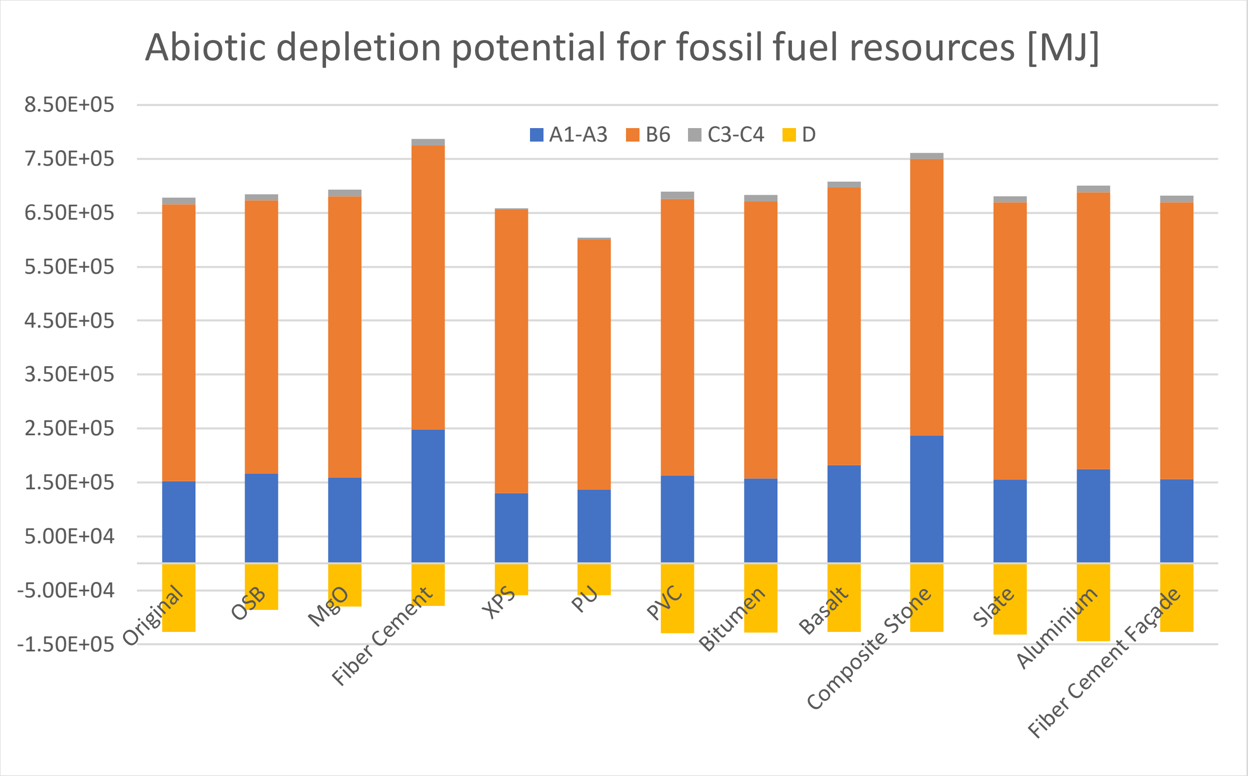

Figure 31 Results per life-cycle stage for abiotic depletion potential for fossil fuel resources

Table 14 Percentage change between the original and alternative designs

	GWP	ODP	AP	EP	POCP	ADPE	ADPF	GWP	ODP	AP	EP	POCP	ADPE	ADPF
	OSB							**Bitumen**						
A1-A3 Embedded costs	-162%	-2%	1%	-3%	10%	-23%	8%	-52%	-17%	-16%	-7%	-2%	-9%	3%
B6 Heating and cooling	-1%	-1%	-1%	-1%	-1%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%
C3-C4 End-of-life	36%	-71%	-31%	-50%	-6%	-32%	-4%	-4%	-14%	-2%	0%	-4%	-8%	0%
D Benefits beyond the system boundaries	36%	0%	15%	9%	17%	18%	32%	-13%	-81%	-34%	-27%	-18%	0%	0%
TOTAL w/o D	-1%	-6%	-1%	-4%	8%	-16%	1%	-2%	-17%	-8%	-3%	-2%	-6%	1%
TOTAL w D	4%	-7%	3%	-4%	10%	-15%	9%	-1%	-4%	-1%	0%	0%	-7%	1%
	MgO							**Basalt**						
A1-A3 Embedded costs	513%	20%	15%	60%	1%	-1%	4%	117%	444%	12%	1%	5%	-15%	20%
B6 Heating and cooling	2%	2%	2%	2%	2%	2%	2%	0%	0%	0%	0%	0%	0%	0%
C3-C4 End-of-life	-72%	27%	-17%	-42%	-1%	-19%	2%	-8%	107%	-6%	24%	55%	-8%	0%
D Benefits beyond the system boundaries	45%	-3%	15%	9%	11%	24%	38%	-1%	-20%	-2%	-11%	-2%	-12%	-1%
TOTAL w/o D	8%	20%	8%	23%	1%	0%	2%	3%	425%	5%	2%	4%	-10%	4%
TOTAL w D	15%	23%	13%	26%	3%	3%	11%	3%	513%	8%	3%	5%	-10%	6%
	Fibre Cement							**Composite Stone**						
A1-A3 Embedded costs	842%	368%	91%	67%	13%	330%	62%	354%	45%	83%	79%	8%	30%	54%
B6 Heating and cooling	3%	3%	3%	3%	3%	3%	3%	0%	0%	0%	0%	0%	0%	0%
C3-C4 End-of-life	-72%	119%	-11%	-39%	12%	-2%	7%	-14%	-7%	-10%	-33%	-5%	-8%	-1%
D Benefits beyond the system boundaries	45%	0%	15%	9%	11%	25%	38%	-1%	-20%	-2%	-11%	-2%	-12%	-1%
TOTAL w/o D	19%	355%	44%	26%	11%	214%	16%	10%	42%	39%	30%	6%	20%	12%
TOTAL w D	29%	425%	59%	30%	13%	250%	29%	11%	54%	49%	34%	7%	24%	15%
	XPS							**Slate**						
A1-A3 Embedded costs	-35%	15%	2%	3%	-54%	1%	-15%	74%	17%	5%	1%	0%	89%	2%
B6 Heating and cooling	2%	2%	2%	2%	2%	2%	2%	0%	0%	0%	0%	0%	0%	0%
C3-C4 End-of-life	-7%	8%	-32%	355%	-55%	-28%	-76%	-14%	-5%	-9%	-33%	-4%	-7%	-1%
D Benefits beyond the system boundaries	33%	0%	41%	43%	57%	41%	54%	4%	97%	13%	24%	3%	364%	3%
TOTAL w/o D	0%	15%	2%	20%	-43%	1%	-3%	0%	16%	2%	-1%	0%	58%	0%
TOTAL w D	4%	18%	13%	27%	-41%	7%	9%	0%	0%	-1%	-4%	-1%	12%	0%
	PU							**Aluminium**						
A1-A3 Embedded costs	4%	2163%	0%	7%	-54%	49%	-11%	172%	-17%	25%	0%	3%	592%	14%
B6 Heating and cooling	-10%	-10%	-10%	-10%	-10%	-10%	-10%	0%	0%	0%	0%	0%	0%	0%
C3-C4 End-of-life	-7%	190%	-12%	1%	-45%	8%	-65%	-14%	-8%	-9%	-33%	-4%	-7%	0%
D Benefits beyond the system boundaries	33%	0%	41%	43%	57%	41%	54%	25%	-22%	56%	29%	24%	18%	13%
TOTAL w/o D	-9%	2056%	-5%	-2%	-45%	28%	-11%	4%	-17%	12%	-2%	2%	383%	3%
TOTAL w D	-5%	2463%	4%	2%	-44%	38%	-1%	1%	-16%	0%	-5%	0%	437%	1%
	PVC							**Fibre cement façade**						
A1-A3 Embedded costs	-30%	17%	-14%	-3%	-2%	8%	6%	90%	23%	5%	-2%	0%	-8%	2%
B6 Heating and cooling	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
C3-C4 End-of-life	0%	320%	32%	10%	14%	129%	10%	-14%	11%	-8%	-32%	-4%	-4%	1%
D Benefits beyond the system boundaries	11%	62%	33%	26%	17%	0%	2%	-1%	-20%	-2%	-11%	-2%	-12%	-1%
TOTAL w/o D	-1%	33%	-6%	-1%	-1%	6%	2%	1%	23%	2%	-2%	0%	-5%	0%
TOTAL w D	0%	52%	1%	2%	0%	7%	2%	1%	31%	3%	-2%	0%	-4%	1%

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