Kaunas University of Technology
Institute of Environmental Engineering
Faculty of Mechanical Engineering and Design

LIFE CYCLE ASSESSMENT OF MAGNESIUM OXIDE STRUCTURAL INSULATED PANELS

Master's Final Degree Project

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Assoc. prof. dr. Daina Kliaugaitė
Supervisor

Kaunas, 2021

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Sustainable Management and Production (6213EX001)

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Life cycle assessment of magnesium oxide structural insulated panels

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Institute of Environmental Engineering

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Master's final degree project

Topic of the project	**Life cycle assessment of magnesium oxide structural insulated panels**
Requirements and conditions (title can be clarified, if needed)	Student are required to investigate the available literature on MgO SIP properties and environmental impacts caused by its production, use and possibilities of reuse-recycle. To perform environmental impact modelling and assessment of the MgO SIP at all stages of the product life cycle, from raw material extraction, panel production, installation, and use to final waste disposal. Based on the obtained results and world science practice in this field, to identify environmental hotspots over entire life cycle of MgO panels and propose improvement potentials associated with end-of-life management scenarios.
Supervisor	Assoc. prof. dr. Daina Kliaugaitė 2021-05-31
	(position, name, surname, signature of the supervisor) (date)

Alonso Soto, Alexandra María. Life cycle assessment of magnesium oxide structural insulated panels. Master's Final Degree / supervisor assoc. prof. dr. Daina Kliaugaitė; Institute of Environmental Engineering; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Environmental Engineering (E03) – main study field, Production and Manufacturing Engineering (E10), Business (L01), Engineering Sciences.

Keywords: structural insulated panel, life cycle assessment, environmental impact, recycling, recovery, magnesium oxide, polyurethane foam.

Kaunas, 2021. Number of pages: 57

Summary

The construction and operation of buildings have significant impacts on the environment. In Europe, buildings account for approximately 40% of energy consumption and 36% of carbon dioxide (CO_2) emissions. The need to build sustainable buildings that use less energy, fewer natural resources, and proper construction materials to be built and operated is a necessity that can be achieved with innovative technologies and the compliance of laws and regulations. Magnesium Oxide Structural Insulated Panel is a construction material with many advantages claimed by its manufacturers: lightweight, fire resistance, high insulation properties and minimization of energy consumption. Nonetheless, far too less information about the impacts to the environment from the raw materials extraction process as well of the recycling options for this component can be found in the literature.

This study presents a cradle-to-grave analysis of the life cycle of MgO SIP that was conducted through the implementation of a life cycle assessment (LCA) methodology for a functional unit of 1 m^2 of insulated panel given a thermal insulation value and within 50-year service life. The study was conducted following the International Organisation for Standardisation (ISO) standards ISO 14040:2006 for life cycle assessment and the European Standard EN 15804:2012+A2 for sustainable building assessment. This study included the evaluation of environmental impacts over all MgO SIP life cycle and recycling/recovery opportunities for the panel after the end-of-life stage and compared it with a baseline scenario. Results indicate that the cycle stages with higher contributions in almost all impact categories are the raw materials production and supply (A1), construction (A5) and end-of-life (module C3) stage. Concerning end-of-life scenarios assessment, results indicate although both alternatives are feasible and produce lower environmental impacts than the baseline scenario, the chemical recycling option provides chemical substances recovery opportunities that can lead to broader secondary raw material applications.

Alonso Soto, Alexandra María. Struktūrinių magnio oksido (MgO) plokščių su izoliaciniu sluoksniu aplinkosauginis būvio ciklo įvertinimas. Magistro baigiamasis projektas Vadovė doc. dr. Daina Kliaugaitė; Kauno technologijos universitetas, Aplinkos inžinerijos institutas; Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Aplinkos inžinerija (E03) – pagrindinė, Gamybos inžinerija (E10), Verslas (L01), Inžinerijos mokslai.

Reikšminiai žodžiai: konstrukcinė izoliuota plokštė, gyvavimo ciklo įvertinimas, poveikis aplinkai, perdirbimas, utilizavimas, magnio oksidas, poliuretano putplastis.

Kaunas, 2021. Puslapių sk. P: 57

Santrauka

Pastatų statyba ir eksploatavimas daro didelį poveikį aplinkai. Europoje pastatai sunaudoja apie 40% energijos ir 36% anglies dvideginio (CO2). Yra būtinybė statyti darnius pastatus, kuriuose sunaudojama mažiau energijos, mažiau gamtos išteklių ir daugiu aplinkai palankesnių statybinių medžiagų. Tai galima pasiekti naudojant novatoriškas technologijas, laikantis techninių reglamentų ir kitų teisės aktų. Magnio oksido konstrukcinė plokštė su izoliaciniu sluoksniu (MgO SIP) yra statybinė medžiaga, turinti daug privalumų, kuriuos deklaruoja jos gamintojai: lengva, atspari ugniai, aukštos izoliacijos savybės ir mažos energijos sąnaudos gamybos metu. Tačiau literatūroje yra labai mažai informacijos apie žaliavų gavybos proceso poveikį aplinkai ir šios konstrukcinės medžiagos perdirbimo galimybes.

Šiame tyrime atleikamas pilnas MgO SIP būvio ciklo vertinimas nuo žaliavų išgavimo iki galutinio sutvarkymo. Vertinamas funkcinis vienetas - 1 m^2 plokštės, su atitinkamomis izoliacinėmis savybėmis ir 50 metų naudojimo terminu. Tyrimas atliktas vadovaujantis Tarptautinės standartų organizacijos (ISO) standartais ISO 14040: 2006, skirtu būvio ciklo vertinimui ir Europos standartu - EN 15804: 2012 + A2, skirtu darnių statybinių konstrukcijų vertinimui. Šis tyrimas apima poveikio aplinkai vertinimą įvairiuose plokštės būvio ciklo etapuose ir panaudotų plokščių atliekų esamo tvarkymo scenarijaus palyginimą su galimais dviem perdirbimo scenarijais. Rezultatai rodo, kad didžiausias poveikis aplinkai sukeliamas žaliavų gamybos, apdirbimo (magnio plokštės ir poliuretano putų) būvio ciklo etapo metu (A1), konstrukcijos etape (A5) and atliekų tvarkymo etape (C3). Perdirbimo scenarijų vertinimo rezultatai rodo, kad nors abi nagrinėtos plokščių perdribimo alternatyvos yra įmanomos ir daro mažesnį poveikį aplinkai nei esamas scenarijus, tačiau cheminio poliuretano putų perdirbimo atveju yra regeneruojamos cheminės medžiagos, kurių panaudojimas turi platesnes galimybes.

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Introduction

The construction and operation of buildings has significant impacts on the environment. Only in Europe, where three quarters of its population live in cities and urban areas, buildings account for approximately 40% of energy consumption and 36% of carbon dioxide emissions [1]. With the rapid increase of people being born and moving to cities, along with the growing concern for global warming and climate change, the need to build buildings that use less energy, fewer natural resources, and more eco-friendly materials to be constructed and operated is an urgent necessity.

Structural Insulated Panel (SIP) is a prefabricated construction component whose manufacturer claims to be an “inherently green product” based on their benefits such as lightweight, optimal thermal performance, minimal wastage, and subsequent labour cost reduction [2]. SIP consist of an insulating thick core foam sandwiched between two layers of rigid material, and they can be used as wall, roof, or floor. Typically, oriented strand board (OSB) is used as skin material of SIP while the core is made of plastic foam such as Extruded and Expanded Polystyrene (EPS), and Polyurethanes (PUR) foam [3].

There is a variety of SIP skin materials depending on their advantages and applications, for instance metal, fibre cement, gypsum, plywood, calcium silicate and magnesium oxide (MgO) sheets [4]. MgO SIP boards are a relatively new innovative and uncommon product outside China that is used as an alternative to conventional sheets. The outperformance potential of magnesium oxide panels is attributed to their energy efficiency during the production process, cost effectiveness, and resistance to flames, water and mold [5]. But despite all the benefits claimed for MgO SIP manufacturers, there is very little scientific data that supports the calculation of the environmental impacts caused by the production of this system.

Life Cycle Assessment (LCA) is a tool used to evaluate the environmental impacts of products, services and organisations, both embodied and consumed, from extraction of raw materials to final disposal [6]. This report investigates the different SIP systems (SIPs) available on the current market and investigates the available literature on magnesium oxide panels and studies on environmental impacts caused by its production, use and possibilities of reuse-recycle. Based upon this research, a LCA of magnesium oxide structural insulated panels will be performed to assess the environmental impacts of its lifespan to determine if this system can be considered a “green” construction material.

Project Object: production, transportation use and end-of-life of magnesium oxide structural insulated panels.

Project Aim

To assess the environmental impacts from cradle-to-grave of magnesium oxide structural insulated panels and propose improvement potentials associated with end-of-life management scenarios.

Project Objectives

- To review the available literature of MgO Structural Insulated Panel, current findings, technology gaps and environmental problems
- To compare the advantages and problems of different materials used to produce Structural Insulated Panels against MgO ones

- To analyse literature on recyclability opportunities for MgO Structural Insulated Panels
- To collect data to perform Inventory analysis for LCA study and to perform the environmental impact assessment through the life cycle of MgO Structural Insulated Panels
- To identify environmental hotspots over entire life cycle of MgO Panels and propose improvement potentials associated with end-of-life management scenarios

1. Literature Analysis

1.1. Environmental Impacts of the Construction Industry on the Environment

As population continues to grow, so it does the construction sector and the use of natural resources, global emissions and contamination (Figure 1). Despite the creation of pacts such as The Paris Agreement where it is demanded the building and construction sector to be decarbonised globally by 2050, efforts to curb emissions seem not to be enough to avoid irreversible damages to the environment. In 2018, the global emissions of buildings was 9.7 gigatons of carbon dioxide ($GtCO_2$) [7].

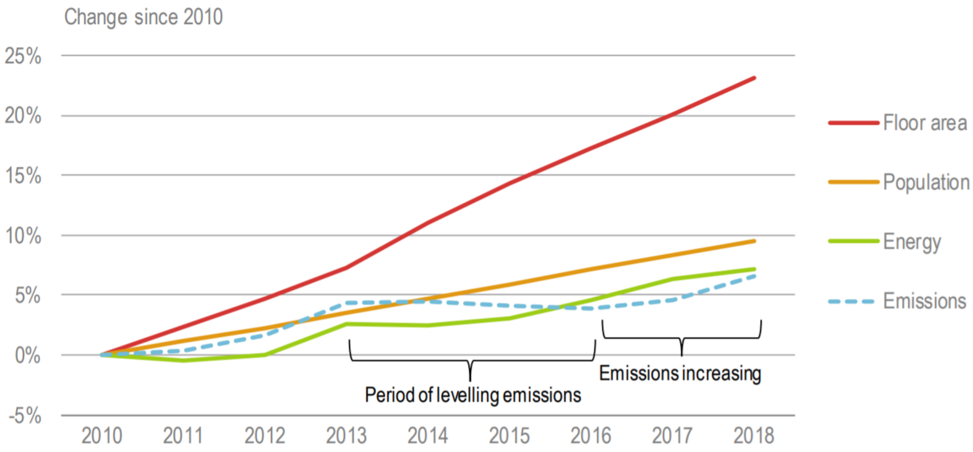


Fig. 1. Changes in floor area, population, buildings sector energy use and energy-related emissions [7].

In 2018, the building and construction industry generated 36% of the world-wide energy use and 39% of CO_2) emissions associated to processes inherent of the sector (Figure 2). In total 11% of CO_2 emissions where attributed to manufacturing the building materials like glass, steel and cement that have high contents of embodied energy [7].

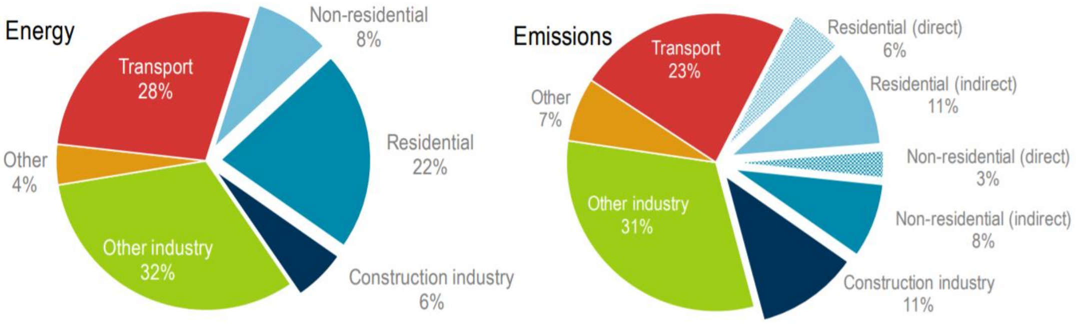


Fig. 2. Construction sector global energy and emissions cut, 2018 [6].

Looking through the entire life cycle of the buildings in Europe, it is estimated that they are responsible of 50% of the total used energy, 40% of the total greenhouse gasses (GHG) emissions, 50% of all the raw material extraction and 33% of all water use [8].

Waste generated from Construction Activities

Besides climate change, land use, water and air pollution, other adverse environmental impacts from this industry are noise, dust, bad odour and solid waste from construction and demolition. Construction and demolition (C&D) waste is output material generated during the process of construction, renovation, or demolition of structures. Factors such as site preparation, damaged material, non-used material and reprocesses due to human error or changes in design are examples of the causes for generation of C&D waste [9] and it can be categorized according to their source, type and complexity as described in the Figure 3. Some hazardous elements like asbestos or liquid waste like kerosene are not included in the scheme due to their nature they are not classified as C&D waste [10].

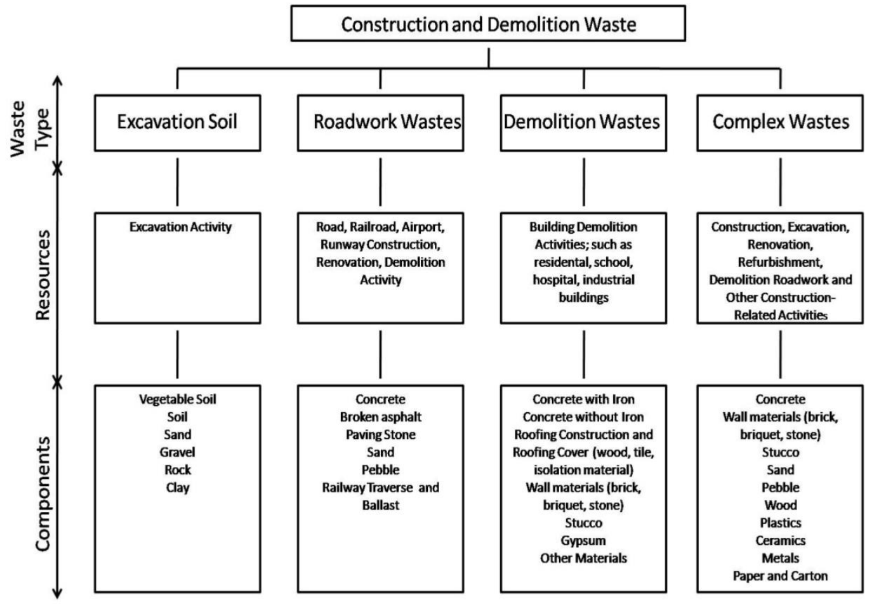


Fig. 3. Types of Construction & Demolition waste [10]

In the year of 2018 in the European Union (EU), construction activities contributed to 36% of all the waste generated from different economic activities and households. Then, mining and quarrying accounted for a 26.6%, manufacturing waste with 10.6%, water services 9.8%, households (8.2%) and the rest (9.1%) was waste from other economic activities like shown in figure 4. [8].

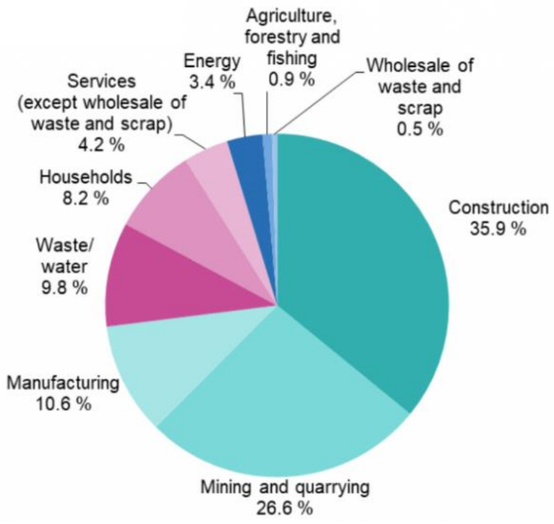


Fig. 4. Total waste generated in EU by economic activities and households, 2018 [8]

In the United States in the year of 2018, 600 million tons of C&D waste were generated, like is shown in Figure 5. The largest material waste was concrete with a 67.5% of the share, then asphalt concrete at 17.8% and wood products with 6.8%. From this total, it is known that over 90% of the C&D waste corresponded to demolition residues while the remaining percentage, that is less than 10%, corresponds to waste from construction processes [10].

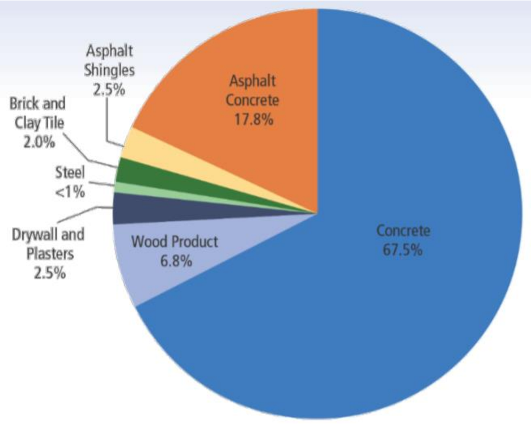


Fig. 5. C&D Waste Generation Composition by Material, 2018 [10]

1.2. Legal Requirements of the Construction Industry in Europe

To have a sustainable future, the construction and building industry must be a larger contributor to that goal by reducing at its lowest all of the impacts from its activities. The Sustainable Development Goals (SDG) were adopted by the United Nations Member States at the Paris Accord (COP21) in 2015 as "an action to end poverty, protect the planet and ensure that people will have peace and prosperity" [11].

There are 17 goals and 169 targets in total, and according to a Study conducted by Sherif Goubran, it was identified that SDG are all in some measure dependent on construction and real estate activities either directly or indirectly [12]. As such analysis is out of the scope of this document, here it is analysed only the relevance of SGD to the construction industry and their importance to minimize environmental impacts, as shown in Table 1.

Table 1. Relevance of Sustainable Development Goals to the Construction Sector [11] [13]

SDG	Why it matters?	Relevance to Construction Industry
SDG 6: clean water and sanitation	Humans need water, sanitation and hygiene to live.	By applying wastewater reclaim technologies the dependency on fresh water can be reduced on a large scale.
SDG 7: affordable and clean energy	A reliable and accessible energy system supports all sectors, including infrastructure.	Design of energy efficient buildings that support their operation using own sources of renewable energies, such as solar panels, reduces energy dependency and reduce operation costs.
SDG 9: industry, innovation and infrastructure	The infrastructure sector and its technological progress generates jobs and social and sustainable development.	Innovation in construction materials and systems helps reducing energy consumption, decreases CO2 emissions and supports design through green buildings certification processes.

SDG	Why it matters?	Relevance to Construction Industry
SDG 11: sustainable cities and communities	Adaptability and resilience of urban areas in adjusting new norms helps to a fast mitigation of extreme events like natural disasters or pandemics, like the current case with Covid-19.	Cities become more resilient when they place less load on natural resources such as water and energy. Designing smart cities that adapt to anthropogenic activities without affecting the ecosystem is a necessity to guarantee a sustainable future.
SDG 12: responsible consumption and production	Economic and social progress should not incur into environmental degradation that endangers of ecosystems on which humans depend on to live	Construction should be built to adapt during its lifespan and design to avoid or minimize at its lowest waste generation and even be a save source for secondary raw materials.

EU is aiming to reduce 85-90% of GHG emissions by 2050 and sustainable buildings play an important role to achieve this goal as they have the potential to lower their emissions at such extent with the adequate investment and management. The EU implemented a legislative and regulatory framework that will be covered in this study for resource efficiency and waste management.

The Energy Performance of Buildings Directive (Directive EU 2018/844) promotes the improvement of the energy performance of buildings. Member States shall stablish strategies to assure that all new constructions will be “Nearly zero-energy buildings” (NZEB) and should renovate each year 3% of central government buildings that do not comply with adequate energy performance. NZEB are those that require nearly zero or very low energy consumption, which they are capable to produce onsite or nearby surroundings from renewable sources [14].

The Renovation Wave is part of the European Green Deal to make EU’s economy sustainable and to achieve the 85-90% GHG emissions reduction. The aim of this strategy is to improve energy performance of existing construction and has set a target of 35 million renovated buildings by 2030. Currently only about 75% of Europe buildings are not energy efficient which is reflected to the fact that around 34 million people in EU are unable to pay for adequate heating for their housing, proving that renovation is fundamental to eradicate energy poverty, and to assure good health and wellbeing of citizens [15].

Circular Economy (CE) “aims to restoration and regeneration by design, to keep products, components and materials at their highest utility and value at all times…” [16]. The **Circular Economy Principles for Buildings Design** document provides bases for the building environment actors for three macro-objectives: to reduce C&D waste, to optimize material use and to reduce environmental impacts of design and material selection along the lifespan. This document is in accordance with the new EC Communication COM (2020) 98 called “*A new Circular Economy Action Plan for a cleaner and more competitive Europe”*. The document was published last November 2020 and refers to the introduction of a “new strategy for sustainability of the built environment material efficiency and climate impact reduction” [17].

Life Cycle Assessment (LCA) in the Construction Industry provide the framework for evaluating potential environmental impacts associated with all the building’s life cycle phases. LCA can be applied to design and construction industry to provide building a way to understand how the buildings can affect the environment depending on how much energy they use [6]. LCA can also be used to evaluate impacts of construction products and their use, such is the case of Environmental Product Declarations (EPDs), a document that communicates information in a credible way about the impacts of they can cause. Such information must be compared with other similar products and verified by private reviewers and is as a way for the company to back-up their products environmental performance [18].

Directive 2008/98/EC on waste was amended on 2018 is part of the EU Action plan for the Circular Economy, which contains important remarks and legislation proposals related to C&D waste and that now includes waste resulting from minor activities of the private households. One of the main purposes of this revision is to motivate EU members to adapt the CE guidelines for construction and waste while trying to cope with the original target of the waste framework that set a 70% by weight of non-hazardous C&D waste to be recycled and re-used by 2020 [19]. To the date only 50% of the C&D waste is being recycled, with a few Member States exception like Germany and the Netherlands which recycling rates for C&D waste is at 90% [20].

1.3. Innovative Construction Materials for Building Envelope

In an effort to reduce the environmental impacts of building materials engineers and scientists around the world are developing alternative materials to traditional ones such as cement, bricks, wood, steel and glass. In this section four of those innovative building materials will are reviewed.

1.3.1. Hempcrete

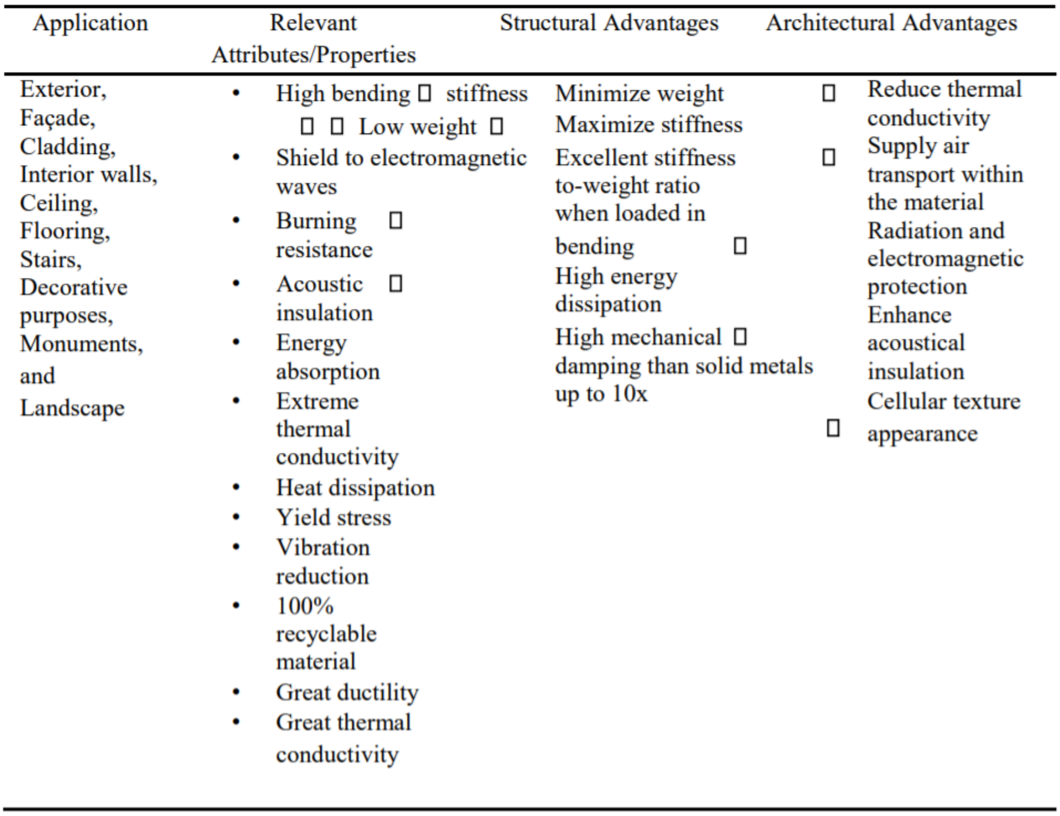
From Fig. 5 it is known the amount concrete waste at a global scale for the year of 2018 was more than 400 million tons. The proportion is logical because concrete is the most common used building material with a yearly production of about 1 m^3 per head of population and estimated generation of 900 kg CO_2/ton of cement produced [21].

Experiments with biomass products as building materials have led to the development of hemp concrete, also referred to as hempcrete, a biocomposite combination of hemp shive, lime binder and water. Hempcrete applications include walls, floors and roofs. Hemp has been cultivated since 8,000 BCE for a variety of purposes. In the field of construction hemp offers carbon sequestration, lightweight, low density, moisture buffer capability, low thermal conductivity and acoustic insulation. Several thermal tests on hempcrete around the world displayed a better insulation rating (R-value) for this material versus cellular concrete. While cellular concrete with a density of 480 kg/m^3 exhibited an R-value of 0.18 Km^2/W, hempcrete showed an R-value of 0.22 Km^2/W with a 400 kg/m^3 density, which means that wit hempcrete less material is needed to provide relative same value of insulation as when using cellular concrete. This can also translate into less energy to produce the material and to install, less weight and eventually less concrete waste [22].

1.3.2. Aluminium Foam

The variety of applications of aluminium foam materials in the building sector have benefits in the environmental and economic aspects. Some important physical and mechanical characteristics of metallic foams are rigidity, low specific weight, high compression strength, and thermal and acoustic absorption. A good application for aluminium foam composites is when used in sandwich panels, since they are capable to absorb energy, vibration and sound, and can be used in high temperature environments [23].

Applications in architecture and construction of aluminium foam are presented in Figure along with its structural and architectural advantages [23].



Application	Relevant Attributes/Properties	Structural Advantages	Architectural Advantages
Exterior, Façade, Cladding, Interior walls, Ceiling, Flooring, Stairs, Decorative purposes, Monuments, and Landscape	• High bending ☐ stiffness ☐ ☐ Low weight ☐ • Shield to electromagnetic waves • Burning ☐ resistance • Acoustic ☐ insulation • Energy absorption • Extreme thermal conductivity • Heat dissipation • Yield stress • Vibration reduction • 100% recyclable material • Great ductility • Great thermal conductivity	Minimize weight Maximize stiffness Excellent stiffness to-weight ratio when loaded in bending ☐ High energy dissipation High mechanical ☐ damping than solid metals up to 10x	☐ Reduce thermal conductivity ☐ Supply air transport within the material Radiation and electromagnetic protection Enhance acoustical insulation ☐ Cellular texture appearance

Fig. 6. Advantages of the Aluminium foam core application [23]

Extra advantages of aluminium relevant to the construction sector are low reaction to corrosion, electrical conductivity, and easy to machine and to recycle, which makes it environmentally friendly and sustainable [23].

1.3.3. Magnesium Oxide Structural Insulated Panels

Structural Insulated Panel (SIP) is a prefabricated construction component with a lifespan of above 50 years, and that has gained interest for its streamlined assembly technology that helps to reduce construction times and subsequently reduces the labour costs. According to the Structural Insulation Panel Association (SIPA), SIP is an “inherently green product” because of its airtightness and high insulation properties leads to less heating and cooling energy consumption, improves control of indoor environmental conditions, and reduces construction waste. SIP is as a sandwich panel that can be use as wall, roof, and floor. The typical SIP arrangement consists of two external layers of rigid material and one thicker inner layer, skin and core, respectively. Skins are traditionally made using oriented strand boards (OSB) and the core or insulation with expanded polystyrene (EPS) or polyurethanes (PUR) foam [2][3].

As sustainability concerns grow in all sectors, the construction industry has also incurred in new technologies and materials to improve building’s energy efficiency and quality. Magnesium oxide (MgO) boards are a relatively new skin material used in the SIP production industry as an alternative for conventional panels materials such as plywood, gypsum pasteboard, fibre cement, among others [24]. It was found that the manufacturing of magnesium boards uses on average 25 to 50 percent of the energy required to manufacture other boards from materials such as calcium hydroxide or Portland cement. It is also known that MgO boards contain no asbestos, ammonia, silica or benzene avoiding the release of hazardous emissions to the air [25].

1.4. Structural Insulated Panels

Structural Insulated Panel (SIP) is a sandwiched prefabricated building system used as wall, roof, and floor for residential and light commercial construction. The first notion of SIP was first presented at the Forest Products Laboratory (FPL) in the USA back in 1935 when it was discovered that hardboard and plywood had wall-like behaviour when bearing structural load [26]. Sandwich panel technology was also used in the aerospace industry in its early stage before becoming popular in the 1960s, when they started being used in several different applications like refrigerated storages and automobile and shipbuilding industries [27].

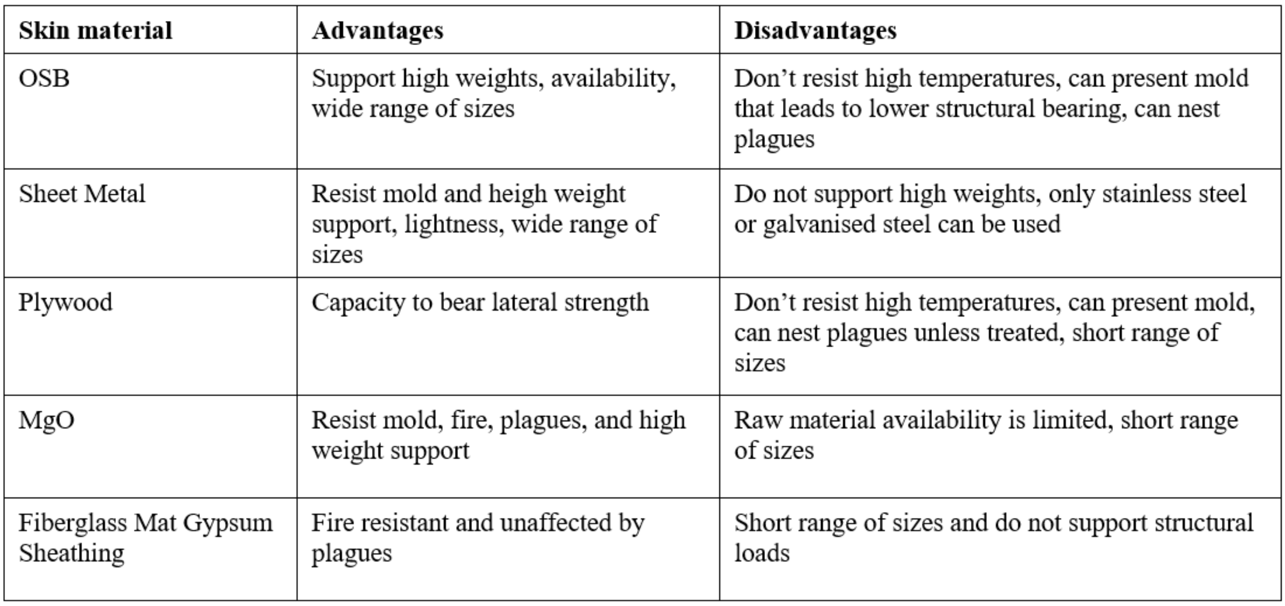
As mentioned in the previous section, SIP typical arrangement consists of two external layers of rigid material and one thicker inner layer. A common SIP configuration is shown in Figure 7, where skins are made with OSB and the core is made with EPS. Another type of sandwich panel are precast concrete sandwich panels (PCSP), that consist of two concrete wythes as skin and lightweight foam as core material. The connection of this board can be made with a steel shear connector, rigid concrete bridge, glass fibre reinforced polymer (GFRP) or carbon fibre reinforced polymer (CFRP) [28] [3].

Fig. 7. SIP common configuration, OSB skins and EPS foam core.

The most commonly used boards OSBs sheet metal, plywood and fibre-cement cladding. In relatively recent years the use of new skin materials such as MgO and fiberglass mat gypsum sheathing have emerged in the market promising improved insulation and environmental benefits compared to the traditional ones [29] [30].

One of the reasons why OSB is more frequently used is because of its lower price and higher load bearing, on the other hand they are not fire resistant and are susceptible to nest insects and rodents. Metal sheets can be very light and load bearing as well better aesthetics, but its elevated heat transfer properties increases the potential of flammability of FRP, which causes SIP non-conformance with fire code requirements. Sheet made of cement, magnesium and fiberglass have higher resistance to mould, but they are also heavier and have limited panel size. There is still need for further research as to what the properties of new materials for SIP are concerned. Table 2 summaries the known advantages and disadvantages of the mentioned skin materials [3].

Table 2. Common Skin Materials, advantages and disadvantages [29] [30]

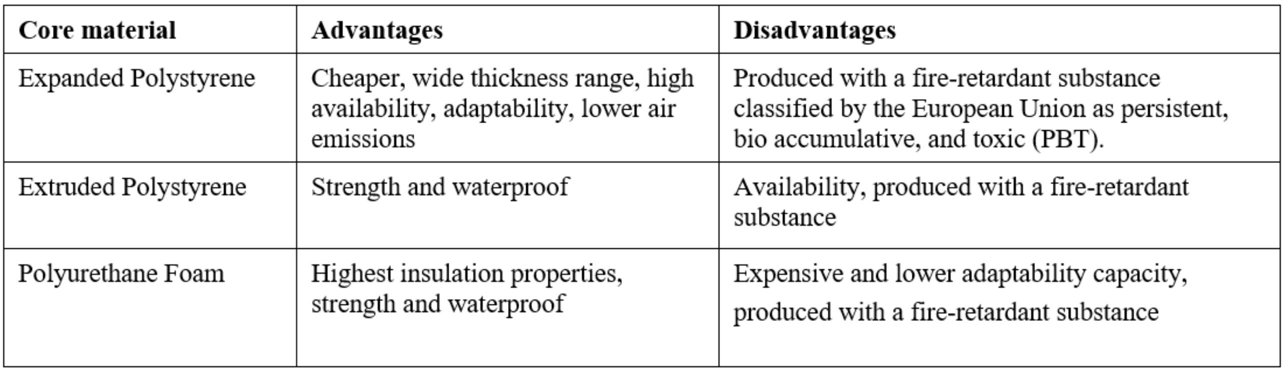


Skin material	Advantages	Disadvantages
OSB	Support high weights, availability, wide range of sizes	Don't resist high temperatures, can present mold that leads to lower structural bearing, can nest plagues
Sheet Metal	Resist mold and heigh weight support, lightness, wide range of sizes	Do not support high weights, only stainless steel or galvanised steel can be used
Plywood	Capacity to bear lateral strength	Don't resist high temperatures, can present mold, can nest plagues unless treated, short range of sizes
MgO	Resist mold, fire, plagues, and high weight support	Raw material availability is limited, short range of sizes
Fiberglass Mat Gypsum Sheathing	Fire resistant and unaffected by plagues	Short range of sizes and do not support structural loads

Common insulation materials for SIP core are non-structural and ridged, like Extruded Polystyrene (XPS) and Expanded Polystyrene (EPS), and Polyurethanes (PUR) foam such as polyisocyanurate and polyisocyanate. A study conducted by [Frostig and Thomsen, 2011] states that PUR foams has better thermal performance against fire and smoke, and that SIPs manufactured using this core material are stronger than those made of EPS against axial, flexural and lateral loads. Another study led by Zia et al. (2007) reviewed different recycling technologies for polyurethane materials, such as mechanical and chemical recycling. They found that with re-bonding, one of the most used mechanical recycling processes, it is possible to obtained new properties of PU such as higher density and lighter hardness. For chemical processes, such as glycolysis, it is possible to regain the polyols that are suitable for manufacturing new PUR foam [31].

Table 3 presents the major benefits and most important drawbacks from common insulation materials of SIPs [30].

Table 3. Common Core Materials, advantages and disadvantages [29] [30]



Core material	Advantages	Disadvantages
Expanded Polystyrene	Cheaper, wide thickness range, high availability, adaptability, lower air emissions	Produced with a fire-retardant substance classified by the European Union as persistent, bio accumulative, and toxic (PBT).
Extruded Polystyrene	Strength and waterproof	Availability, produced with a fire-retardant substance
Polyurethane Foam	Highest insulation properties, strength and waterproof	Expensive and lower adaptability capacity, produced with a fire-retardant substance

SIPs are considered as smart industrial building systems (IBS), that is a construction which components are manufactured in a location different to the installation site, and that can be installed with low on-site work [32]. The streamlined characteristic of SIPs provides advantages of minimum material wastage, less use of additional material for installation, controlled quality, faster project completion, and lower total construction costs. According to SIPA, SIP building have around 85% more air tightness potential than wood-frame buildings which helps reducing energy consumption and subsequential operational costs [2]. SIP insulation material have excellent thermal insulation properties and are not very susceptible to external temperatures fluctuations, so buildings can stay warmer in winter and cooler in summer, reducing the necessity of artificial heating and cooling [33].

1.5. Life Cycle Assessment

Most of the energy certification processes for buildings are awarded based on the operational phase of the buildings and far too little attention is directed to the materials that conform them and to the handling of waste at the end of their service life. In a globalized economy where products and goods can be purchased from any country or continent, materials like cement, concrete, metals and plastics can be used in the building environment without increasing production costs but that may lead to higher environmental impacts associated with their transportation and large-scale extraction of raw materials [34]. Life Cycle Assessment methodology analyses the entire life cycle of a system, product or service to attempt to perform a quantitative and/or qualitative assessment of the impacts that those can cause on the environment, in the society or in the economy [6].

The leading standards for LCA are ISO 14040:2006 and ISO 14044:2006. LCA principles and Framework for conducting and reporting an LCA are provided in the ISO 14040, while ISO 14044 covers more detailed procedures and examples in requirements and guidelines for conducting an LCA. The results from a LCA study can be useful inputs to a variety of decision-making processes. In the Figure 8, the four phases that comprise LCA studies are presented: goal and scope definition, inventory analysis, impact assessment and interpretation [35].

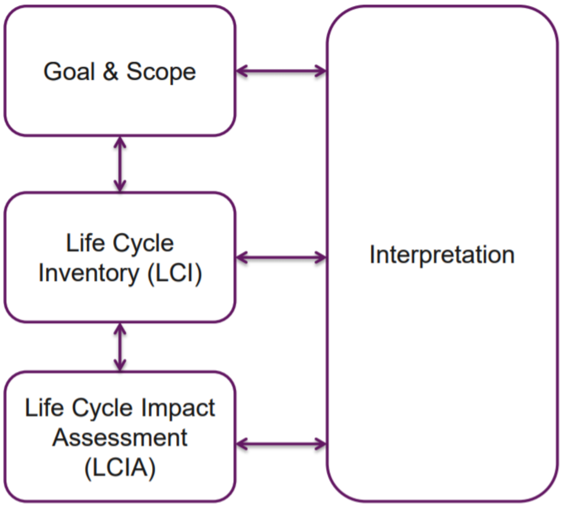


Fig. 8. Four stages of life cycle assessment methodology framework according to ISO 14040

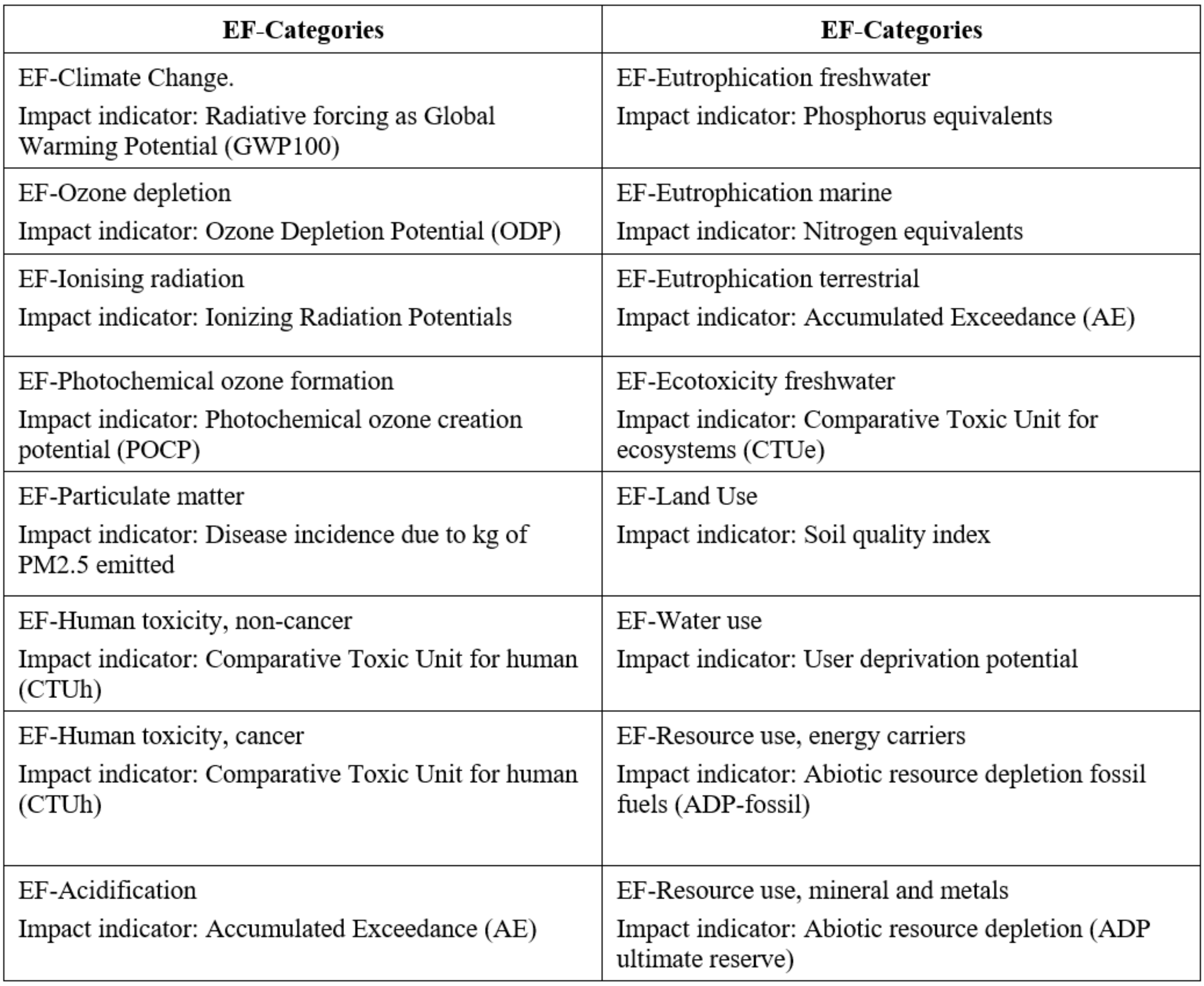
The **Goal definition** determines and defines the purpose of the study, and the **scope definition** determines what product systems will be evaluated and how this assessment should take place. The goal defines the aim of the study and the scope defines the breadth and depth of the study. In the goal must be stated what is the intended application and why the study is being carried out, as well the planned audience and whether the results are intended to be used in comparative assertions or disclosed to the public [35] [36].

During the **Life Cycle Inventory (LCI)** analysis the data for the processes is collected to later create the model flows of the product system. The result from this phase is a list of quantified elementary flows that cross the system boundary of the life cycle and it becomes the input of the next phase of the study. LCI is an iterative process and more and/or new data can be entered as more is learned about the system during the modelling process. This could even lead to a revision of the goal and/or scope if necessary [35] [36].

Life Cycle Impact Assessment (LCIA) phase results in the evaluation of the significance of potential environmental impacts based on the LCI results. Elementary flows are quantities that not always can be comparable within each other, therefore is necessary to follow at least three mandatory steps to do so: selection of impact categories, category indicators, assignment of LCI results and characterisation. The impacts that are assessed during this phase should be interpreted as impact potentials and not as definite impacts [35] [36].

The characterisation step can be done at different pathways of the LCA study, either at midpoint or endpoint levels. ***Midpoint impact category*** offers indicators for comparison environmental interferences at a level of cause–effect chain of an impact category, before to the endpoint level. ***Endpoint impact category*** provides indicators at the level of protection areas such as natural environment's ecosystems, human health or resource availability. In practice, category indicators are combined into predefined methods that are available in LCA software such as ReCiPe, CML, TRACI, EF, etc., which should be chosen depending on the approach selected to perform the LCIA, qualitative or quantitative. Table 4 shows the impact categories analysed in the EF method [35] [36].

Table 4. EF method impact categories [Source: SimaPro, Ecoinvent database]



EF-Categories	**EF-Categories**
EF-Climate Change. Impact indicator: Radiative forcing as Global Warming Potential (GWP100)	EF-Eutrophication freshwater Impact indicator: Phosphorus equivalents
EF-Ozone depletion Impact indicator: Ozone Depletion Potential (ODP)	EF-Eutrophication marine Impact indicator: Nitrogen equivalents
EF-Ionising radiation Impact indicator: Ionizing Radiation Potentials	EF-Eutrophication terrestrial Impact indicator: Accumulated Exceedance (AE)
EF-Photochemical ozone formation Impact indicator: Photochemical ozone creation potential (POCP)	EF-Ecotoxicity freshwater Impact indicator: Comparative Toxic Unit for ecosystems (CTUe)
EF-Particulate matter Impact indicator: Disease incidence due to kg of PM2.5 emitted	EF-Land Use Impact indicator: Soil quality index
EF-Human toxicity, non-cancer Impact indicator: Comparative Toxic Unit for human (CTUh)	EF-Water use Impact indicator: User deprivation potential
EF-Human toxicity, cancer Impact indicator: Comparative Toxic Unit for human (CTUh)	EF-Resource use, energy carriers Impact indicator: Abiotic resource depletion fossil fuels (ADP-fossil)
EF-Acidification Impact indicator: Accumulated Exceedance (AE)	EF-Resource use, mineral and metals Impact indicator: Abiotic resource depletion (ADP ultimate reserve)

In the **Interpretation** phase the findings from the inventory analysis and the impact assessment are considered simultaneously to provide the outcomes in form of conclusions and recommendations, that should be consistent with the goals and scope of the study [6] [35] [36].

LCA study results enables all actor involved in the product or service to make decisions considering all the environmental media that conforms the entire life cycle stages. LCA also enables the identification of hotspots during each life cycle stage and supports the creation of alternative solutions to avoid transferring burdens from one stage to another, from one geographic area to another and from one environmental media to another, for example from water to land [37].

Limitations of LCA must be considered throughout the process. LCA studies are based on assumptions and scenarios that simplify real problems that may occur during real world processes, especially because not always al data can be included and evaluated during the analysis. As LCA studies can have different scopes, assumptions and scenarios, the results are also different and hardly comparable among each other, which can result in confusing information specially for people without previous knowledge about the methodology. Additionally, the entire LCA data gathering and processing may be highly time consuming and if it happens that the information collected is not accurate or simple poor, the conclusions and recommendations at the end of the study will not be precise as well.

1.5.1. Life Cycle Stages of structural insulated panels

Sustainability measures of construction work and services is a necessity to reach the energy efficiency goals of the building industry set by the European laws and regulations [36]. The Standard 15804:2012+A2:2019 ‘Sustainability of construction works’, provides core product category rules (PCR) for the LCI and LCIA, including the level of data quality to be used and the rules for reporting predetermined, environmental and health information. [38]. Ultimately, the goal of the document is “to provide the basis for assessing buildings and other construction works and identifying those which cause less stress to the environment”.

SIPs are construction materials which manufacturers claim to be an inherently green product, so the standard 18504 can be used to assess their environmental impacts through all the life cycle stages of the panels, from raw materials extraction, production, use and end-of-life. Additionally, a module for supplementary information beyond the product life cycle such as reuse, recovery or recycling potential can be included in the analysis to inform about potential benefits outside the system boundary, as depicted in Figure 9.

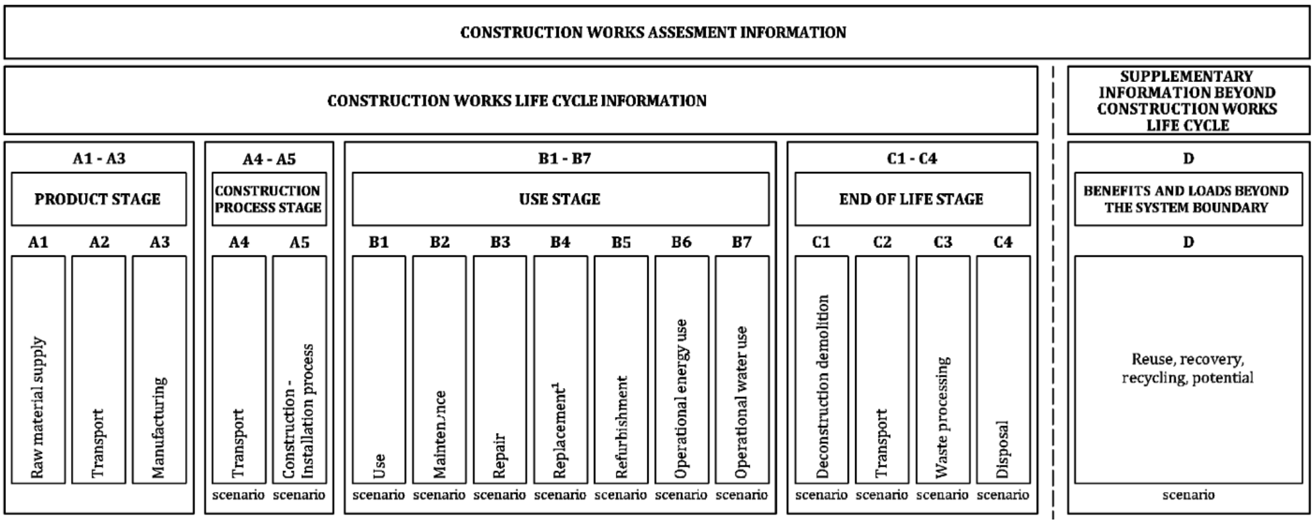


Fig. 9. Construction products assessment based on life cycle stages covered and modules (15804:2012+A2:2020) [36]

1.6. Magnesium Oxide Structural Insulated Panels

Magnesium oxide boards are being used as alternative to traditional skin materials such as plywood, gypsum plasterboards and fibre-cement boards. The first uses of magnesia mixed into mortar are recorded in constructions such as the Great Wall of China and the Roman Empire [39]. But as construction builders turned to cheaper materials the use of magnesia declined and it was only until two decades ago that magnesia has started to be used again because of its sustainability, structural and versatility properties.

MgO SIP consist of two skins of MgO boards and a core that can be made from extruded polystyrene, expanded polystyrene, polyisocyanurate foam, polyurethane foam, or be composite honeycomb (HSC). Production processes for MgO SIP can be different depending on the manufacturer, but generally it is done on a semi-automated production line where panels and core are bonded together using some type of adhesive, like polyurethane along with pressure from a pneumatic press with a force of around 800 kg/m^2 [40].

The process to fabricate MgO boards consists of mixing MgO powder with water, chloride, salts, cellulose, perlite and other aggregate materials, which results in a dense liquid mixture. The liquid is then poured onto a casting tray and then passed through a series of rollers to spread it out evenly across the mould to form the paste into the desired thickness. Next, the board is cured at ambient temperature for at least 24 hours before being removed from the mould to finally be cut to the desired dimensions. MgO powder is obtained by calcinating magnesium carbonate ($MgCO_3$), also referred to as magnesite, at temperatures of around 700 °C. China, North Korea and Russia owns almost 65% of the global magnesite resources [40] [41] [42].

Among the different types of core materials analysed in Table 3, polyurethane (PU) foams offer the best insulation and a very high protection for moisture and sound transferring. PU foam can be rigid (PUR), flexible or semi-flexible. PUR is produced by reacting di-isocyanates and polyols, that are both products derived from crude oil. Acetone is used as an auxiliary blowing agent. The first result is a non-foamed liquid mixture which is afterward retained in bulk form for a dwell time during which an exothermic reaction occurs and the liquid foams. The liquid is then spread onto a surface allowing it to expand and form the solid polyurethane foam material. [43] [44]

MgO sheet sizes are similar to those of drywall and they can be produced in various forms with thickness going from ranges of 6mm to 25mm (¼” to ¾”). Although MgO boards can be used in the same way as Portland cement or gypsum, substitution is not fully direct as thicknesses, fastening methods and joint treatments are not entirely the same [40]. Besides the already mentioned properties and advantages of MgO SIP in prior sections, it’s worth mentioning that this material is water-resistant, do not release volatile organic compounds (VOC) gasses and they offer superior fire suppression compared to OSB boards.

Compared to traditional concrete production processes, the manufacture of MgO requires lower temperature for calcination. While Portland cement production temperature is around 1,450 °C the one for reactive MgO calcination temperature is 700 °C, that outcomes into a smaller environmental footprint [45]. When mixed into cement, MgO is capable to store CO2 as solid carbon minerals, a process called mineral carbonation. In a study conducted by Power I. M et al, in 2017, it was found that magnesium oxychloride cement (MOC) is capable to offset between 20-40% of the emissions generated during the calcination process over a period of 15 years [46].

Another significant advantage of MgO SIP is that their skin and core materials can be recovered and/or recycled. The process of separating MgO from the foam, binder materials and any type of reinforcement starts when the panel is grinded in the waste processing facility. Then, an air separator separates the materials in light and heavy fraction materials, as the MgO, foams and reinforcement have different densities facilitating the process [47]. MgO in pieces “is not classified as Persistent, Bio accumulative and Toxic (PBT) or very Persistent and very Bio-accumulative (vPvB) substance, according to EU criteria” [48] and can be used as secondary raw material to produce fertilizer [49].

Despite all the advantages stated for MgO by its manufacturers, other studies conducted in Europe have also studied some disadvantageous cases of the material's performance. In a study conducted by Gravit et al., In 2017, it was found that moisture formation can appear in MgO wallboards under special climatic conditions, which can lead to subsequent corrosion of frames and origin of mold on architectonic details like wood [50]. Another experiment conducted by Nicholas Jays in 2017, concluded that there is a significant variation of MgO boards in the market and stated that those showing damages due to dampness “may be attributed to the process of magnesium oxychloride and its nature to absorb moisture from the air” [51].

1.6.1. Research Studies on Life Cycle Assessment of MgO SIP

Li at al., (2018) [52] conducted a LCA on a prototype high-performance house built with MgO SIP in Vancouver to investigate the environmental impacts of the product against traditional stick-frame. In terms of energy consumption during the construction phase, they found that a traditional stick-frame house of the same area as the prototype will use the same diesel input for the forklift operation that translates into same environmental burdens. For the operational phase, they found that the energy used for heating in the prototype house was lower due to better thermal insulation of SIP compared to stick-frame. The MgO used in the prototype house was transported more than 9,000 km from China to Canada, this contributed significantly to a poor overall environmental performance of this SIP compared to stick-frame, so only when MgO can be produced locally it could potentially show advantages relative to conventional construction materials.

Another LCA conducted by BASF Corporation [53] compared the environmental impacts of four different insulation systems for residential housing in the USA: SIP using EPS, SIP using PUR foam, and 2x4 wood stick-frames and 2x6 wood stick-frames, both with fiberglass insulation. For this research, transportation distances were set at approximately 800 km from manufacture to jobsite, except for wood which was set at 320 km. Results show that SIP has lower impacts than wood stick-frames and have higher cost benefits thanks to the reduction in heating and cooling loads, as shown in Figure 10, where 1.0 represents the worst position (the lower the score, the higher the eco-efficiency). While in both Li et al., and BASF Co studies, SIP performed better that stick-frame in terms of energy consumption for operational phase and waste reduction, the overall poor results exerted by transportation distances show that in order to classify a construction material as "green" their total life cycle span must be evaluated in the assessment of their environmental impacts.

Since SIP are manufactured in the factory a significant reduction of waste is generated during the manufacturing and construction process where most of it accounts for packaging materials [3]. Depending on the type of skin, recyclability potential of SIP can be significantly high. Metal skins such as steel can be 89 percent recycled at the end of life [46], both PUR and PIR can be recycled through melting and regrinding. Scrap from EPS generated during the manufacturing of boards can also be recycled into new EPS products [2] [3]. As MgO is an innovative material in SIP technologies there is still no scientific evidence of waste management other than landfilling, therefore recovering, recycling or reuse scenarios during life cycle has been excluded from LCA studies [51].

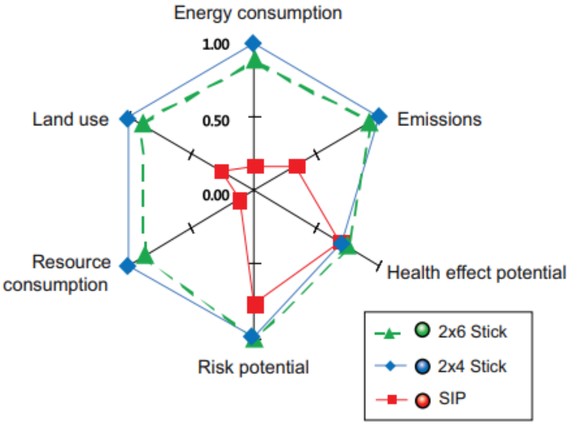


Fig. 10. Overall ecological footprint results by insulation system [53].

1.7. Conclusion

According to the literature reviewed in this section, the high emissions generated by the building sector can be significantly reduced through the implementation of appropriate building materials. The analysed studies on MgO SIP indicate that its use can improve the energy performance of buildings. In addition, its manufacturing process uses lower temperatures than those required to produce other more conventional materials such as Portland cement, which means lower CO_2 emissions and operational costs. However, the carried-out research does not provide clear results of the environmental impacts that MgO SIP can cause during the extraction and transportation of raw materials and at the end of its lifespan, and neither provide information about the benefits of recycling options of MgO. It is proposed in this document to conduct a study to assess the cradle-to-grave impacts of MgO SIP and to propose recycling scenarios which results can lead to improvements at the end-of -life management stage.

2. Methods

As described in the prior section, the International Organization for Standardisation (ISO) provides principles, framework, requirements, and guidelines to complete life cycle assessments through ISO 14040:2006 and ISO 14044:2006 [35] [36]. This study is based on the standard ISO 14040:2006 and EN 15804:2012+A2:2020 sustainability for construction processes and products to identify the environmental impacts of the life cycle phases of MgO SIP. Prior to this study, a company manufacturing this construction material must be selected to obtain the input-output data necessary to conduct the LCA.

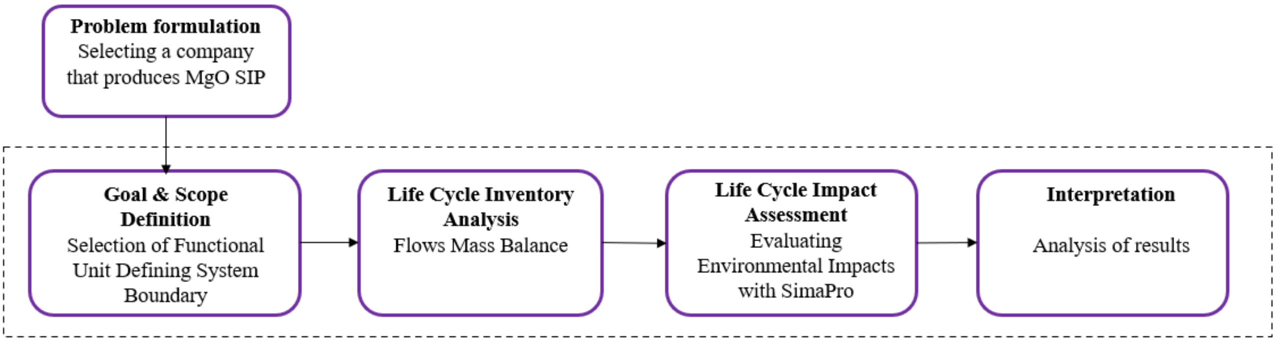


Fig. 11. Life cycle assessment methodology flow chart

In this step it is necessary to identify a company that produces MgO SIP to obtain the quantitative information of the flows that conform the production process of the panels. To define the relevant inputs and outputs associated with the life cycle stages of the panel will be described based on the normative of the standard 15804, presented in the Figure 11.

About the selected company and description of the life cycle of the panel

A company with base in Northern Europe producing MgO SIP is selected to conduct the LCA study. All information concerning materials and processes hereafter presented, unless otherwise specified, was provided by the selected company.

The SIPs are produced with MgO skins and PUR foam core, and with the option to include pultruded reinforcement profiles in between the layers for higher rigidity. Panels are available in different thicknesses, but for the purposes of this study an intermediate thickness value is selected.

The production process of the panels starts with the cutting, if needed, of the MgO boards which will be used as the outer layer (skin) of the panel using an industrial saw. The boards are then reinforced by multidirectional short fibres and tapes manually laminated on the board where it is required by dimensioning studies. Boards and profiles are then moved to the press where they are placed inside of a mould and glued together, boards as outer skins and profiles as frames. After that, the mould is closed, and the insulating foam is sprayed into the void between the two boards. Once the foam has set, the panel is removed and set aside to continue the curing process. Finally, the panel is moved to a pallet, and packed using plastic film, plastic belt and corner carton to protect them during the delivery to site.

On-site, panels are discharged using forklifts and installed manually with the necessary ancillary materials, and then fastened with screws.

During the use phase the panels do not require any additional energy input nor maintenance. Through its service life (50 years), the product does not need any repair or replacement.

For this study, end-of-life stage is divided in for modules: deconstruction, transportation to waste processing facility, waste processing, recycling and/or final disposal.

Detailed description of the modules considered for the LCA study along with the necessary assumptions an exemption are presented in further sections.

2.1. Life Cycle Assessment

The software SimaPro 9.1 was used during the LCIA phase to evaluate the possible environmental impacts of the object of study. The software analyses the entered data that is defined within the system boundaries in terms of the selected functional. The software delivers the results of the environmental impacts for the categories selected for this study.

Goal and Scope

To define the goal and scope of the study, the production process of MgO SIP is analysed and the data from the manufacturer is reviewed to determine the specific essential information. The study main objective is to assess the cradle-to-grave environmental impacts of magnesium oxide structural insulated panels, identify hot spots and to find solutions to increase the environmental performance of MgO panels.

System Boundary

This study covers the life cycle stages from cradle-to-grave and module D. The system boundaries for MgO SIP include the raw material processing (module A1), packaging and transportation to manufacturing facility (module A2), production process of the panel (A3), transportation of panel to the construction site (module A4), construction works (A5) and use of the panel for 50 years (modules B1-B7). Deconstruction process of the SIP (module C1) is also included followed by transportation to the waste processing facility (module C2). Here, the panel is treated so all material suitable for recycling or recovery is separated (module C3), the rest will go to the final disposal (module C4). All benefits and loads from waste recycling or reuse were evaluated in model D. Figure 12 represents the entire life cycle phases of the MgO SIP.

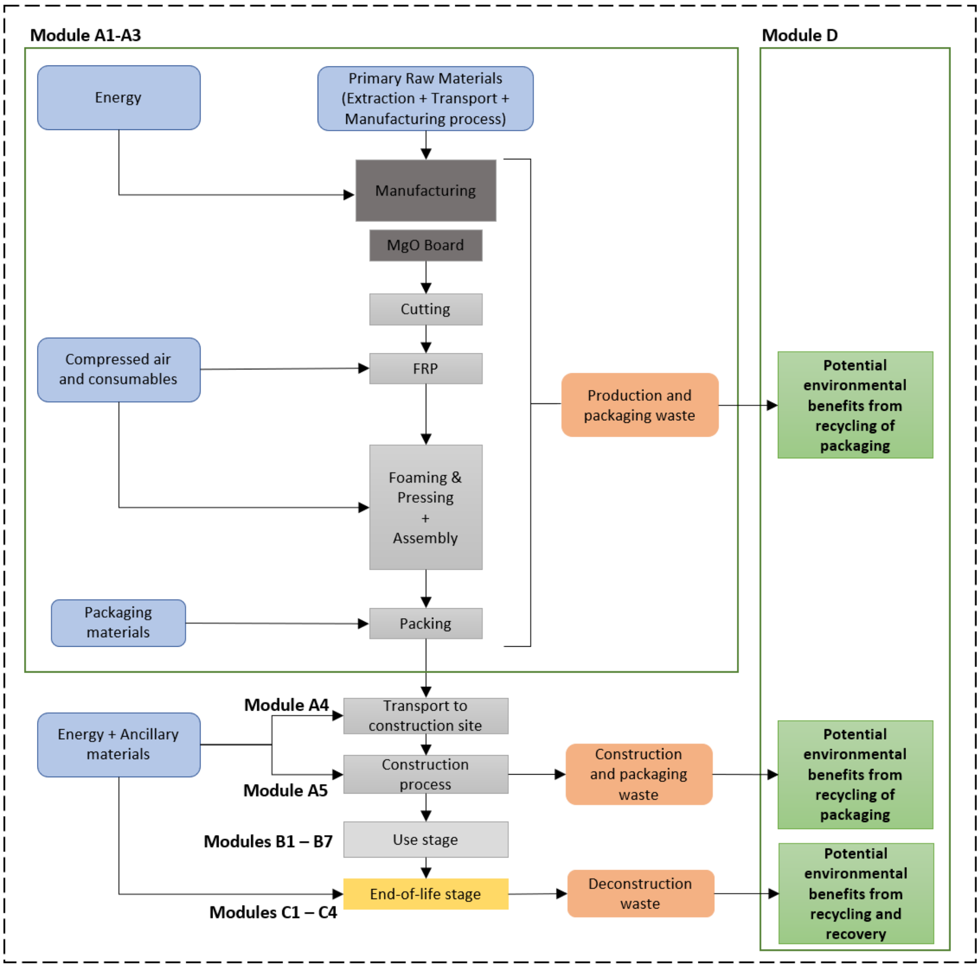


Fig. 12. System boundary chart flow for MgO SIP

Functional Unit

The functional unit for the LCA study is defined as **1 m^2 of insulating panel given the thermal insulation value and within 50-year service life.** Schematic representation of the panel is illustrated in Figure 13. Measures of the selected panel, weight, thickness and insulation value is summarised in Table 5.

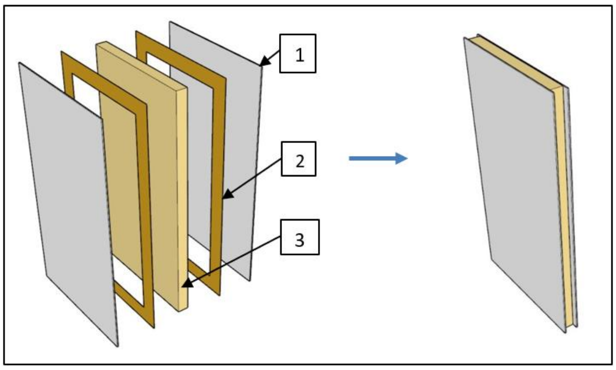


Fig. 13. MgO SIP and components assembly

Where:

1. MgO boards
2. Reinforcement with polyester resin
3. Rigid polyurethane foam

Table 5. MgO SIP global characteristics

Measures		**Thickness**		**Panel**		**Insulation**
Length	Width	Global	MGO	Weight	Weight /m2	U-Value
m	m	mm	mm	kg	Kg/m2	W/m2 K
3	1.22	141.16	10	86.14	23.53	0.187

2.1.1. Life Cycle Inventory Analysis and Description of Life Cycle Stages

During the life cycle inventory (LCI) stage it is defined the relevant inputs and outputs associated with the production, transportation, and use of raw materials and ancillary materials. Inputs include the raw material from extraction, any compound added during production, energy used during production, transportation systems and distances of materials to and from production site. Table 6 specifies the number of raw materials that conform the panel by percentage of composition.

Table 6. Raw material of the product by percentage of composition

Material	**Composition percentage, %**	**Composition weight, kg**
MgO	73.4	18.0
Foam	24.1	5.91
E glass	1.22	0.30
Pol resin	1.30	0.32
Total		24.53

Module A1-A3

The raw materials supply section considers the extraction and processing of all raw materials, pre-products and energy which occurs upstream to the studied manufacturing process. In case of MgO SIP panels the core materials are MgO board and polyurethane foam that are obtained in a controlled chemical reaction during the production process. Raw materials and pre-products products are mostly transported to production sites by road. The use of other materials varies depending on the type of the panel being manufactured and are presented in the table below.

Table 7. Raw materials transportation methods and distances

Material	**Vehicle (Truck/Boat)**	**Utilisation capacity, %**	**Type of vehicle**	**Distance, km**
MgO board	Truck	100	Truck, EURO5, 28-34t	3,479 km (Europe)
Mat E glass	Ship	100	Container Ship	19,959 km (Asia)
Polyester	Truck	100	Truck, EURO5, 28-34t	2,167 km (Europe)
Isocyanate	Truck	100	Truck, EURO5, 28-34t	1,828 km (Europe)
Polyol	Truck	100	Truck, EURO5, 28-34t	1,828 km (Europe)
MgO board	Truck	100	Truck, EURO5, 28-34t	3,479 km (Europe)

The construction process stage includes manufacturing of products and also on-site activities such as storing, mixing, packing and lifting. Use of electricity, fuels and auxiliary materials in the production is considered too. The environmental profile of these energy carriers is modelled for local conditions.

The product stage of the panel occurs as described at the beginning of this section and the quantities shown in Figure 14 are calculated by m^2 of MgO SIP, that is the functional unit.

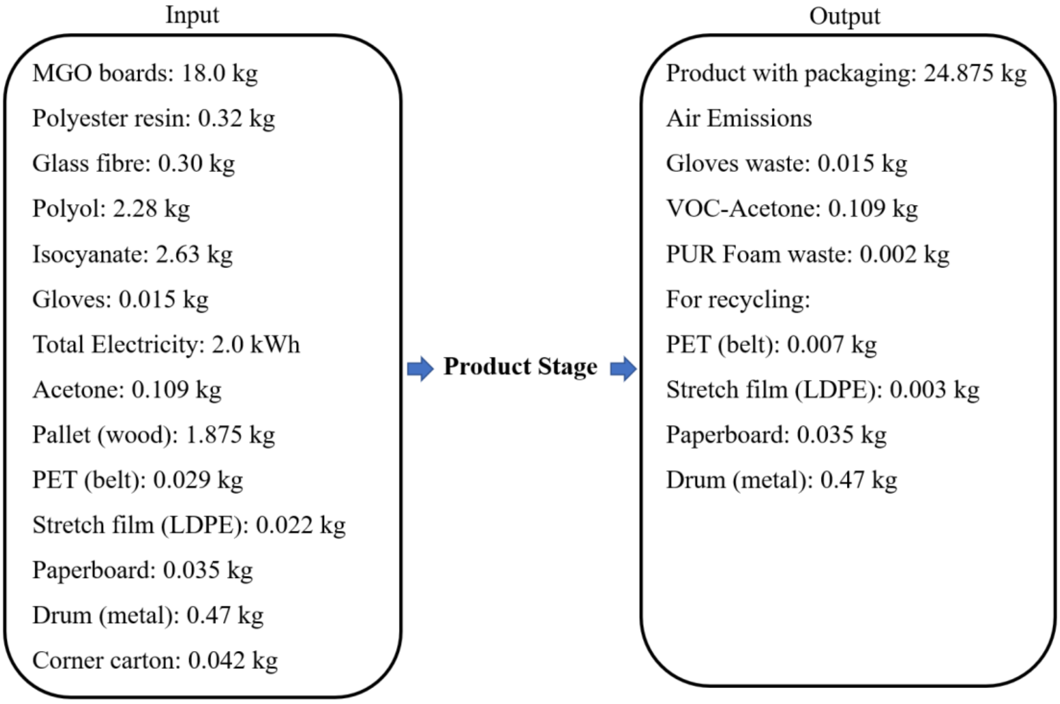


Fig. 14. LCI of production stage

Module A4-A5

Product main destinations are Scandinavia and Europe. Depending on the final destination, the panels are transported with trucks and/or ships.

Table 8. Transportation methods and distances from production to construction site

Material	Vehicle (Truck/Boat)	Utilisation capacity, %	Type of vehicle	Distance, km
MgO SIP	Truck	100	Truck, EURO5, 28-34t	195 km (Northern Europe, 30%)
	Ship/Boat	100	Truck, EURO5, 28-34t	791 km (Scandinavia, 50%)
	Truck	100	Container Ship	1,435 km (Europe, 20%)

There is no storage of products and no wastage of construction product during installation stage. This module include the installation of the product into the building, as well the manufacturing process and the transportation of ancillary materials and energy required for installation or operation in the construction site. Panels are lifted crane run by on site electricity. Ancillary materials like screw and joint materials are used for connecting the panels each other. Module A5 also considers site-related packaging materials production, but excludes potentials benefits and loads of packaging recycling, that is considered in module D.

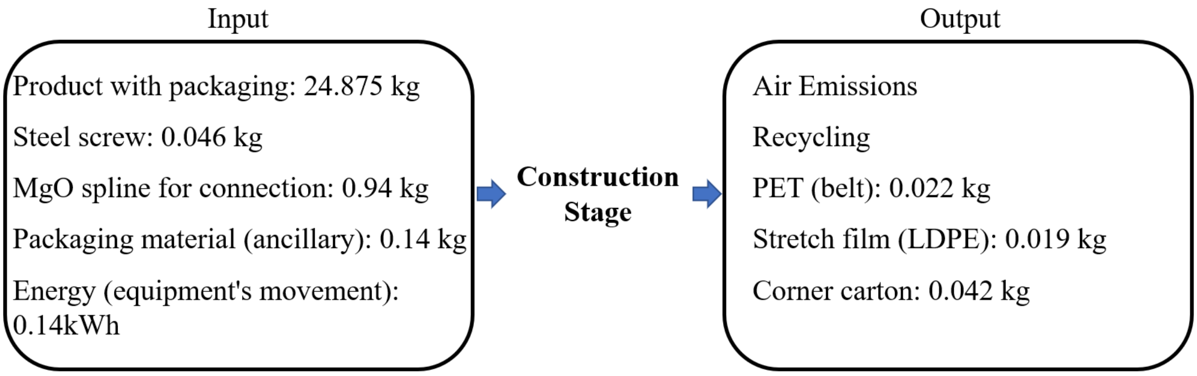


Fig. 15. LCI of construction stage

Module B1-B7

After installation, the product does not require any energy input for its use nor does its maintenance after its commissioning. Through its service life (50 years), the product does not need any repair or replacement, unless external factors cause any damage. Repainting and necessary water for washing that the final user may decide to do is not considered in this module. Any kind of energy utilised for the building operation, such as for heating, cooling, ventilation lighting and domestic hot water, are not within the scope of this study.

In the use stage (B1) calculations for carbonation is considered. The calculations were performed based on the results of a study conducted Power I. M et.al, 2017 [46]. Although the values of offset CO2 emissions are not included in the result tables for environmental impacts, it is worth mentioning why B1 stage is included within the system boundary of the LCA study.

Module C1-C4

According to existing EU waste management regulation, after their use the panels become mixed construction and demolition waste and attributed to waste code „17 09 04“. There is limited empirical evidence of what the end-of-life scenario would be after use of MgO SIP, therefore, the current waste management statistics in Lithuania were followed. According to statistics, during the year 2019 in Lithuania, 353,829 tons of mixed construction and demolition waste was generated. From that amount only 6% was sent directly to landfill, and the remaining amount was processed, sorted and reused (mineral fraction to gravel, broken and crushed stone, plastic, metals, paper, textile, wood).

The end-of-life stage is divided into the following modules:

- Deconstruction – C1: At the end-of-life, in the deconstruction phase, 100% of the waste is assumed to be gathered as separate construction waste and sent to the nearest waste treatment plant for grinding and separation and later to final processing. It is classified as ‘non-hazardous waste’ according to the European list of waste products. The impacts from fuels used for dismantling and emissions of particulates are included in calculation.
- Transport to waste processing – C2: This stage includes impacts generated during the transportation of waste to the treatment plant, where the material is grinded and separated (assumed distance 100 km and utilization 50%). The transportation impacts from the different fractions of waste to the recycling or final disposal place is also included in this module (assumed distance 100 km and utilization 50%). For the transport process it was used the “unspecified market for transportation” category. This activity represents a generic activity

(average of Euro 3,4,5,6 norms) which should be used when no information regarding the transport (lorry size and euro class) is available.

- Waste processing – C3 (baseline scenario): After grinding and separation, several fractions of waste are received: MgO board waste and foam waste and other residue waste (GFRP profile, E-glass, polyester). MgO board waste is considered to be used as gravel or broken and crushed stone for road constructions or concrete aggregates. The remaining fraction is considered to be 50% landfilled and 50% incinerated (final disposal). Energy needed for grinding, separation and PUR recycling are included in this stage and additional materials used for PUR recycling.
- Waste processing – C3 (recycling scenario): After grinding and separation, three fractions of waste are received: foam waste, MgO board waste and residue waste. Foam waste is considered to be converted in to recycled material, MgO board waste recovered to mineral fertilizer and remaining fraction considered to be 50% landfilled and 50% incinerated (final disposal). Energy needed for grinding, separation and foam recycling are included in this stage and additional materials used for foam recycling.
- Final disposal –C4: The impact of disposal of remaining fraction is considered according scenario: 50% incineration and 50% landfilling. Scenario is estimated based on EU statistics, data on plastic production from Plastics Europe. This market dataset models the disposal mix for 1 kg of waste polyurethane and 1 kg of plastic mixture in Europe using countries-specific data. The mix is composed by the following technologies: 1% of open dump, 2% of unsanitary landfill, 47% of sanitary landfill, 50% of municipal incineration.

The baseline of end-of-life scenario of MgO SIP has been defined according with the construction sector national statistics on waste management. It is assumed that MgO board as mineral is separated and reused, and the rests incinerated and landfilled. The end-of-life baseline scenario is presented in Table 9:

Table 9. End-of-life scenario for baseline study

No.	**End of life process flow**		**Waste amount % (part of f.u.)**	**kg/f.u.**
1.	Collection process	Collected as mixed construction and demolition waste	99.8%	26,56 kg
		Collected separately	0.02%	0.0461 kg steel screw
2	Transportation	Transportation from demolition to waste processing and separation	99.8%	Assumed transportation distance 100km, utilization 50%
3.	Grinding and Separation	Collected as mixed construction and demolition waste	99.8%	26,56 kg All collected mixed construction and demolition waste going to grinding and separation
4.	Losses	Loses through processing or transport activities at modules C1 and C2 (end of life)	5%	1,33 kg it is assumed that loses through processing or transport activities are limited to 5%
5.	Transportation	Transportation from processing and separation to recycling,	95%	Assumed transportation distance 100km, utilization 50%

No.	End of life process flow		Waste amount % (part of f.u.)	kg/f.u.
		recovery, reuse or to final disposal		
6.	Recycling, recovery, reuse	Re-use	70 %	17.8 kg, MgO board for road construction Recovery rate (RR) – 0.95
		Recycling	0.02%	0.0461 kg steel screw recycling rate (RR) – 0.5
7.	Disposal	Municipal incineration share	15%	3.7 kg PUR, GFRP, polyester, E-glass) (Recovered energy: 3,92 MJ/kg electric energy or 7,66 MJ/kg thermal energy) Recovery rate (RR) – 0.90. Typical rate for thermal process efficiency.
		Landfill share	15%	3.7 kg PUR, GFRP, polyester, E-glass

In the light of current trends, the strategic Green Deal directions of the EU and based on review of the scientific literature and hot spot analysis of this study, a decision has been made to choose alternative scenarios recycling and recovery scenario/scenarios, presented in Table 10 and Table 11, respectively.

Table 10. Alternative scenario (recycling scenario) with PU recycling and MgO board reuse as mineral fertilizer

No.	End of life process flow		Waste amount % (part of f.u.)	kg/f.u.
1.	Collection process	Collected as mixed construction and demolition waste	99.8%	26,56 kg
		Collected separately	0.02%	0.0461 kg steel screw
2	Transportation	Transportation from demolition to waste processing and separation	99.8%	Assumed transportation distance 100km, utilization 50%
3.	Grinding and Separation	Collected as mixed construction and demolition waste	99.8%	26,56 kg All collected mixed construction and demolition waste going to grinding and separation
4.	Losses	Loses through processing or transport activities at modules C1 and C2 (end of life)	5%	1,33 kg it is assumed that loses through processing or transport activities are limited to 5%
5.	Transportation	Transportation from processing and separation to recycling, recovery, reuse or to final disposal	95%	Assumed transportation distance 100km, utilization 50%
6.	Recycling, recovery, reuse	Recovery	70 %	17.8 kg, MgO board to recovery and use of MgO, MgCl2, expanded perlite as mineral ferilizer Recovery rate (RR) – 0.95 Recycled content – 100%

No.	**End of life process flow**		**Waste amount % (part of f.u.)**	**kg/f.u.**
		Recycling (chemical)	19.3 %	5.14 kg foam converted into raw recycled material polyol Recycling rate (RR) – 240% - from 1 kg of PUR waste it could be produced 2.4 kg of recycled polyol (additional chemicals are used) Recycled content in new product – 30%, Recovered polyol can substitute up to 20-40% of conventional polyol for production of rigid PU/PUR foam [31]
		Recycling	0.02%	0.0461 kg steel screw Recycling rate (RR) – 0.95
7.	Disposal	municipal incineration share	3%	1 kg GFRP, polyester, E-glass (Recovered energy: 3,92 MJ/kg electric energy or 7,66 MJ/kg thermal energy) Recovery rate (RR) – 0.90. Typical rate for thermal process efficiency.
		landfill share	3%	1 kg GFRP, polyester, E-glass

Table 11. Alternative scenario (re-bonding) with PU recycling and MgO board reuse as mineral fertilizer

No.	**End of life process flow**		**Waste amount % (part of f.u.)**	**kg/f.u.**
1.	Collection process	Collected as mixed construction and demolition waste	99.8%	26,56 kg
		Collected separately	0.02%	0.0461 kg steel screw
2	Transportation	Transportation from demolition to waste processing and separation	99.8%	Assumed transportation distance 100km, utilization 50%
3.	Grinding and Separation	Collected as mixed construction and demolition waste	99.8%	26,56 kg All collected mixed construction and demolition waste going to grinding and separation
4.	Losses	Loses through processing or transport activities at modules C1 and C2 (end of life)	5%	1,33 kg it is assumed that loses through processing or transport activities are limited to 5%
5.	Transportation	Transportation from processing and separation to recycling, recovery, reuse or to final disposal	95%	Assumed transportation distance 100km, utilization 50%
6.	Recycling, recovery, reuse	Recovery	70 %	17.8 kg, MgO board to recovery and use of MgO, MgCl2, expanded perlite as mineral ferilizer Recovery rate (RR) – 0.95 Recycled content – 100%

No.	**End of life process flow**		**Waste amount % (part of f.u.)**	**kg/f.u.**
		Recycling (re-bonding)	19.3 %	5.14 kg foam converted into raw recycled PUR material Recycling rate (RR) – 0.95 (additional chemicals are used) Recycled content in new product – 30% (indicative assumptions)
		Recycling	0.02%	0.0461 kg steel screw Recycling rate (RR) – 0.95
7.	Disposal	municipal incineration share	3%	1 kg GFRP, polyester, E-glass (Recovered energy: 3,92 MJ/kg electric energy or 7,66 MJ/kg thermal energy) Recovery rate (RR) – 0.90, Typical rate for thermal process efficiency.
		landfill share	3%	1 kg GFRP, polyester, E-glass

Figures 16, 17 and 18 are presented to provide an alternative representation of the end-of-life scenarios proposed in tables 9, 10 and 11, respectively.

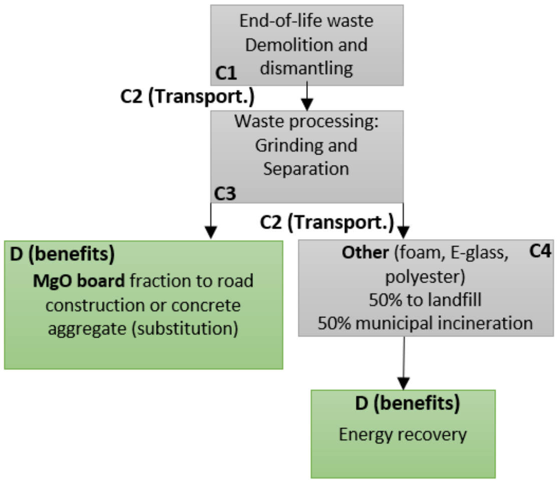


Fig. 16. End-of-life scenario for baseline study

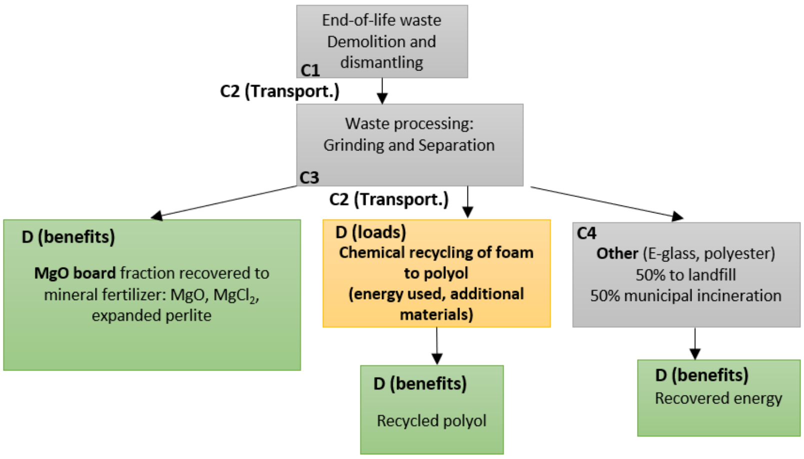


Fig. 17. Alternative scenario (recycling scenario) with PU recycling and MgO board reuse as mineral fertilizer

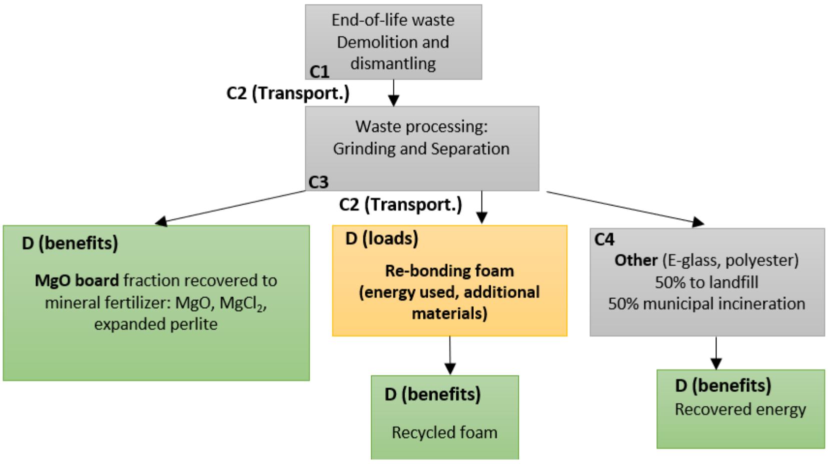


Fig. 18. Alternative scenario (re-bonding) with PU recycling and MgO board reuse as mineral fertilizer

Module D

It is used to declare the potential environmental benefits deriving from the recycling and recovery of the product or parts thereof, outside the boundaries of the system under study. Here, the loads and benefits from the packaging recycling in A1 and A5 and end-of-life scenarios were considered.

A1 and A5 packaging recycling generated benefits from recycling of packaging materials such as: plastic, paperboard .and steel

At the end of life, the MgO SIP panels generates two flows of materials whose treatment can give rise to environmental credits:

- PUR converted into recycled raw material. PUR can be recycled; the recycled material obtained is used as secondary material for the production of new PUR, reducing the consumption of virgin raw materials.
- MgO board converted into mineral fertilizer (MgO, MgC2, Perlite) in “recycling scenario” and into gravel material “baseline scenario”.

2.1.2. Life Cycle Impact Assessment

For the life cycle modelling of the panel system, the SimaPro 9.1 Software and the Ecoinvent 3.6 database is used. To ensure comparability of results in the LCA, the basic data of the Ecoinvent database was used for energy, transportation and auxiliary materials. Where available, specific data derived from the company production processes were the first choice to use; where not, information is obtained from scientific literature.

The software SimaPro provides multiple impact assessment methods to categorize the inventory list into environmental impacts. For these LCA, the EN 15804 EF3 V1.1 midpoint assessment method is used to characterize and categorize the results into the environmental impact categories. The A2:2019 revision of 15804 standard methodology is aligned with the EF 3.0 method, except for their approach on biogenic carbon. According to the EN 15804, “biogenic carbon emissions cause the same amount of Climate Change as fossil carbon but can be neutralized by removing this carbon from the atmosphere again”.

With the ReCiPe endpoint assessment method, the life LCI results are transformed into a limited number of indicators scores, which express the relative severity on an environmental impact category

[54]. There are three endpoint indicators: damage to human health, ecosystems and resource availability, as explained in section 1.5.

2.2. Cut-off criteria, data and processing modelling assumptions

The study comprises all industrial processes, starting from raw material acquisition, passing through production, distribution, and end-of-life stages. All inputs and outputs of the unit processes with available data were included in the calculation. The production of equipment needed to installation, manufacturing, construction activities, as well as human activities related to the processes, energy and water use are not here included.

Specific data derived from company production plant in Europe, corresponding to the year 2020-2021, has been used to inventory the manufacturing phase. For the rest of the phases and process data are generic and come from Ecoinvent v.3.6 database (no data is more than 10 years old). Most of the generic data for processes impact modelling was found in the Ecoinvent database, only the information concerning MgO board production was missing. Therefore, the information concerning composition and electricity of MgO board production was taken from specific Environmental Product declaration (EPD) and available scientific literature [55].

Electricity data source for A3, A5 and end-of-life modules was taken from Ecoinvent database v.3.6 database, market group for electricity, medium voltage electric mix modelled for Europe without Switzerland, data for year 2015. Market groups represent a 'market of markets'. Their purpose is to group a set of markets into larger, geographically relevant datasets. They only group other markets and/or market groups contained within their geography.

Packaging materials information is reported and allocated to the module where it arises. Packaging materials are considered 100 % collected and recycled. Wooden pallets are considered reused and as the role of it in total results is small it was not included in packaging waste treatment impacts calculations.

In module A2 vehicle capacity utilization factor was assumed to be 1, which means full load. Empty returns are not considered as it is assumed that return trip is used by transportation company to serve needs of other clients. In module C2 empty returns are considered and utilization factor assumed to be 0,5.

3. Results and discussion

3.1. Life cycle assessment of MgO Structural Insulated Panel life cycle

The LCIA characterisation results of Climate change category for all the life cycle stages of the MgO SIP are presented in Table 12. Complete information is presented in the Table 21, in the appendices.

Table 12. Impact results for MgO SIP, Method: EN 15804 +A2 Method V1.00 / EF 3.0 Modules A-D-Climate change category

Impact category	**Unit**	**Total**	**(A1-A3)**	**(A4)**	**(A5)**	**C1**	**C2**	**C3**	**C4**	**D total**
Climate change	kg CO2 eq	93.09	66.61	0.88	18.57	0.11	1.4	0.87	11.79	-7.15E+0

Figure 19 shows the relative contributions per module for the selected impact categories per functional unit of the MgO SIP. The main stages with environmental burdens in all impact categories throughout the life cycle of the MgO SIP are product stage (A1-A3), construction stage (A5: installation) and end-of-life stage (C4: disposal). Modules A4 (Transport), C1-C3 (Deconstruction, transport, waste processing) have smaller contributions to each impact category. Module D (Recovery, reuse, recycling potential) negative values represent the environmental benefits that derived from the recycling and recovery from packaging of materials utilised in modules A1 and A5, and end-of-life scenarios proposed in tables 9, 10 and 11. From the figure 20 we can identify the impact categories most affected during the life cycle of the MgO SIP, which are climate change, ecotoxicity-freshwater, resource use – minerals and metals, and particulate matter.

Product stage, or module A1-A3, accounts for 60-80% of every impact in almost all categories, mainly because of the MgO board and the foam production process, as depicted in figure 22. The production process of MgO, methylene diphenyl diisocyanate (MDI), polyol and glass fibre have relative contributions of 40%, 22%, 18% and 16%, correspondingly, of the Climate Change impact category, and have the also large impacts to ecotoxicity-freshwater, resource use-minerals and metals and particulate matter.

Modules A4 and C2 represent lower impacts compared to Module A2 because the transportation distances from the production to construction site, as well from the construction site (after demolition) to waste treatment facility, are much less than distances from raw material supplier to manufacturing site. Impacts of module A5 (construction phase) can be partly attributed to the emissions of nitrogen oxides (NOx) from the diesel combustion used to power forklift trucks and the crane. Yet, the main environmental burden of module A5 is the manufacturing of ancillary materials for installation such as MgO connections, glass fibre reinforcement and PUR, especially because the of glass fibre production emits CO_2 and sulphur oxides (SO_x) as well as thermal NO_x [56]. This impact could be reduced when utilising different connectors for the installation, like glue, considering that recycling of the SIP is possible through mechanical or chemical processes.

The total amount of GHG emissions in kg-CO2-eq is 93.03, and this result can decrease when considering the carbonation process that occur for MgO during a time period of 15 years, with a mean value of 0.07 kg CO_2/m^2/year. For the functional unit defined in this study, where two boards of MgO of $1m^2$ each are used, the amount of stored CO_2 is 2.1 kg.

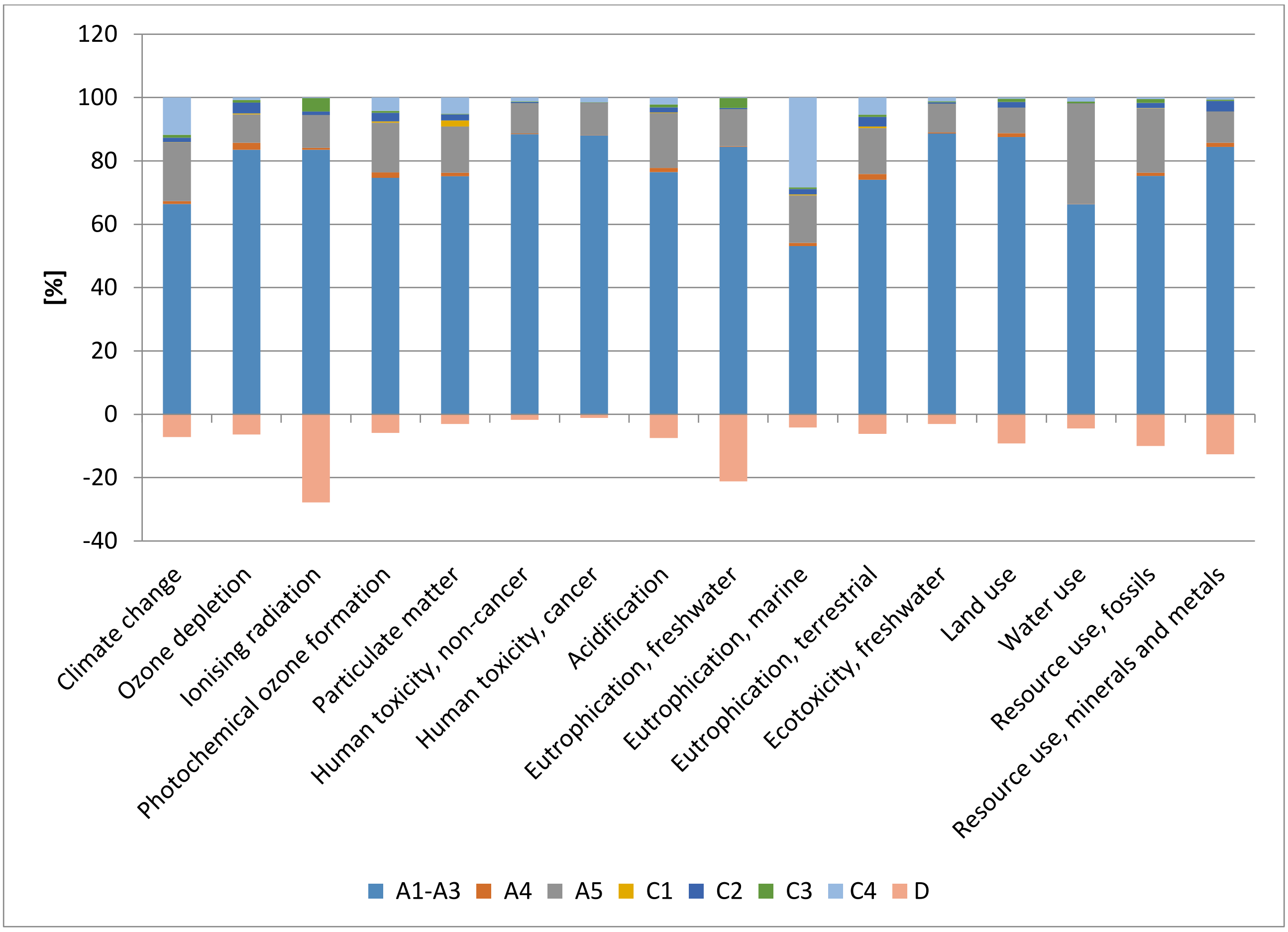


Fig. 19. Characterisation of impact results of MgO SIP, Method. EN 15804 +A2 Method V1.00 / EF 3.0 Modules A-D

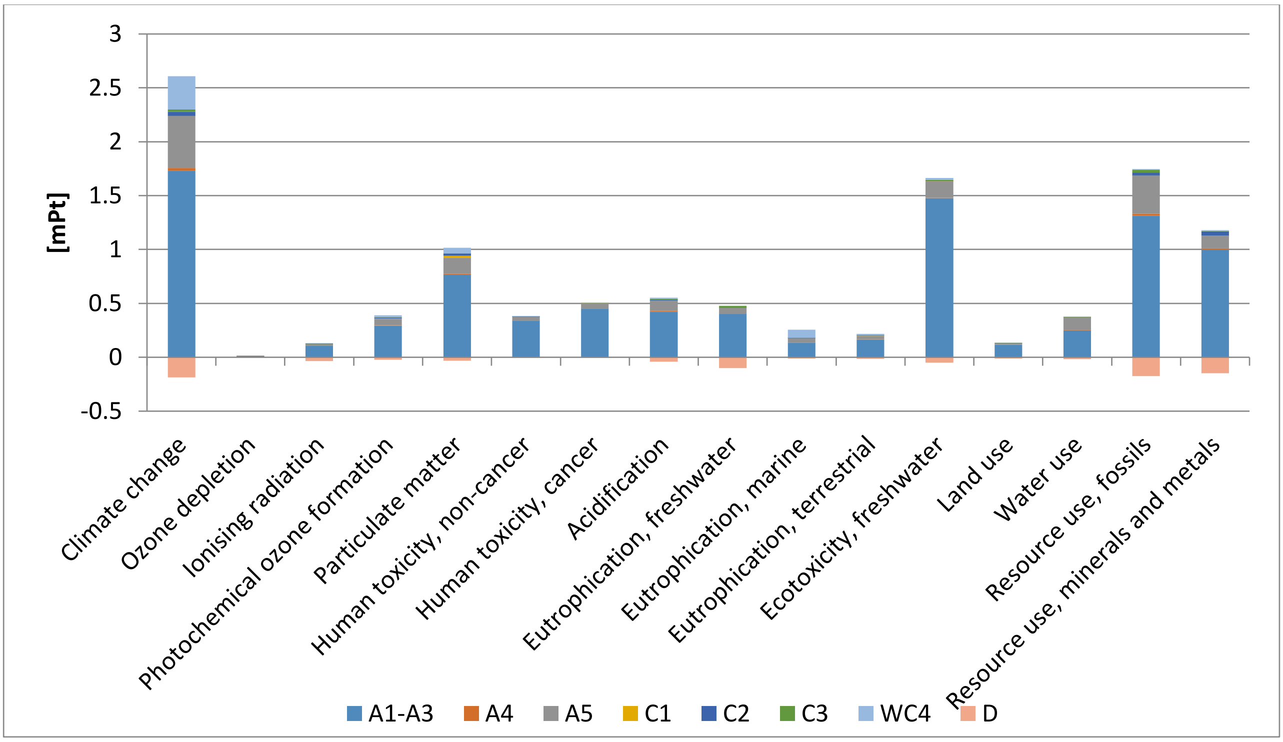


Fig. 20. Normalisation+weighting of impact results of MgO SIP. Method: EN 15804 +A2 Method V1.00 / EF 3.0 Modules A-D

The damage assessment that was calculated using the endpoint indicator method, shown in Figure 20, indicates that the impact caused to human health by modules A1-A3 significantly surpasses the damages to ecosystems and resources, as a result of the GHG emissions from the MgO SIP production process, including its raw materials.

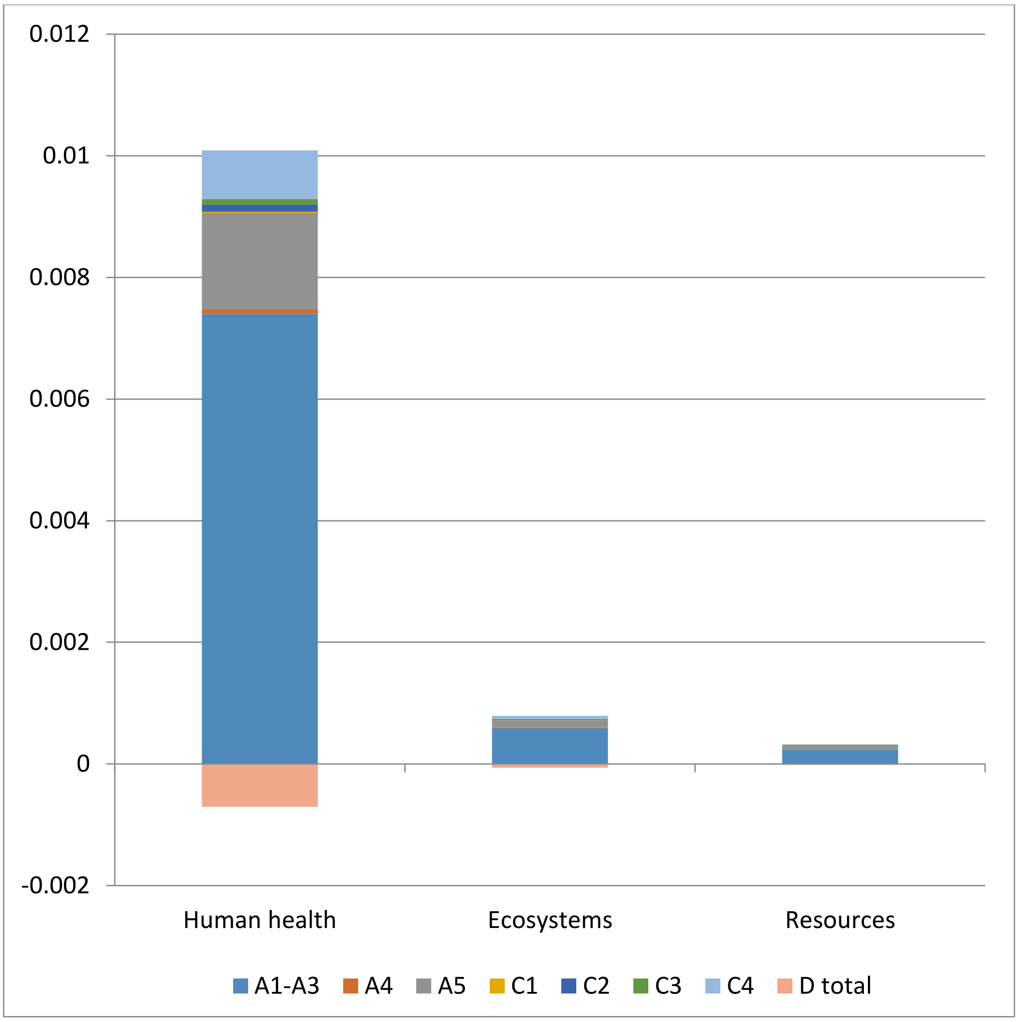


Fig. 21. ReCiPe endpoint method for modules A-D

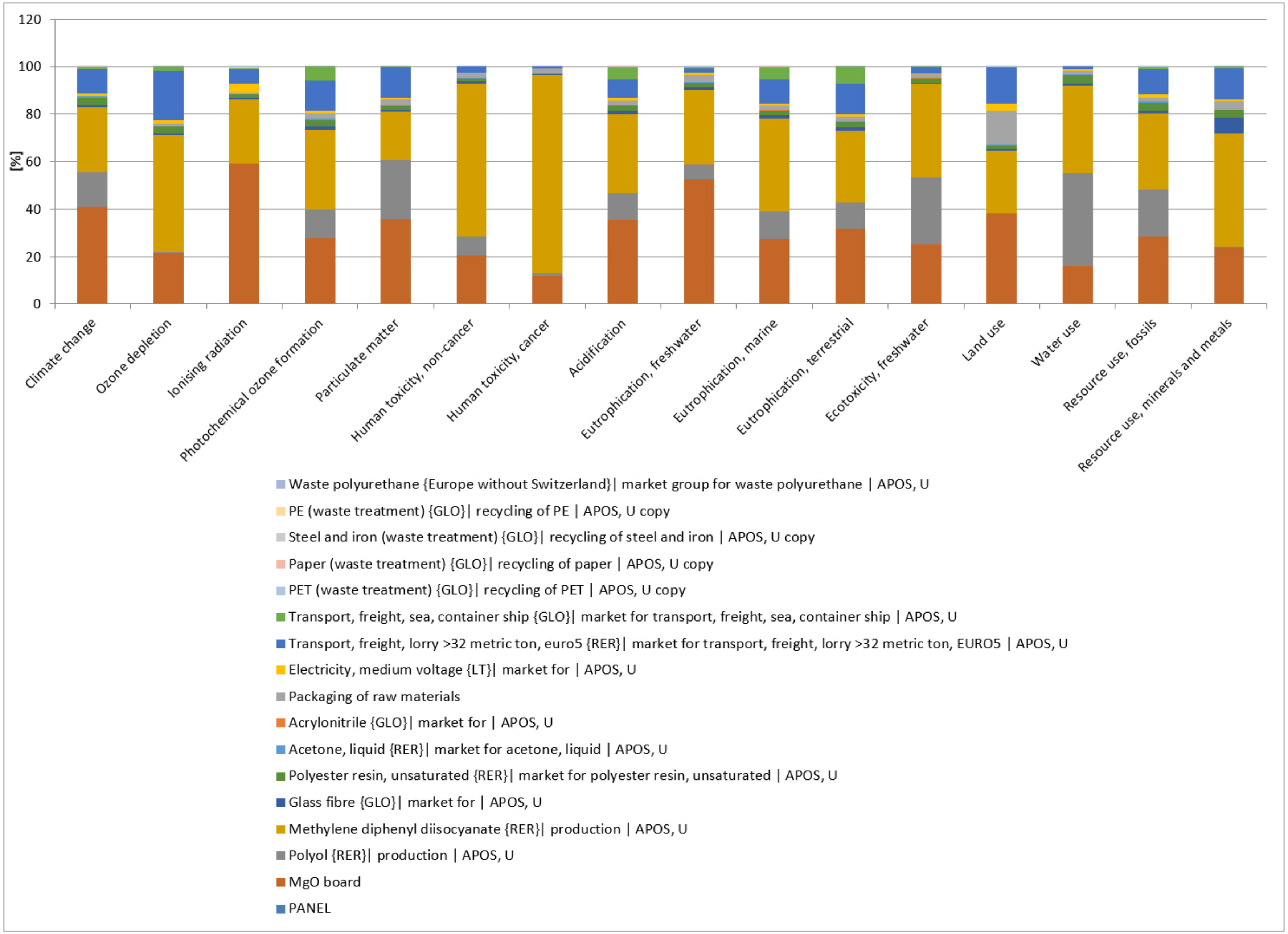


Fig. 22. Characterisation impact results for unpacked MgO SIP (A1-A3), Method: EN 15804 +A2. Method V1.00 / EF 3.0, 23.5 kg

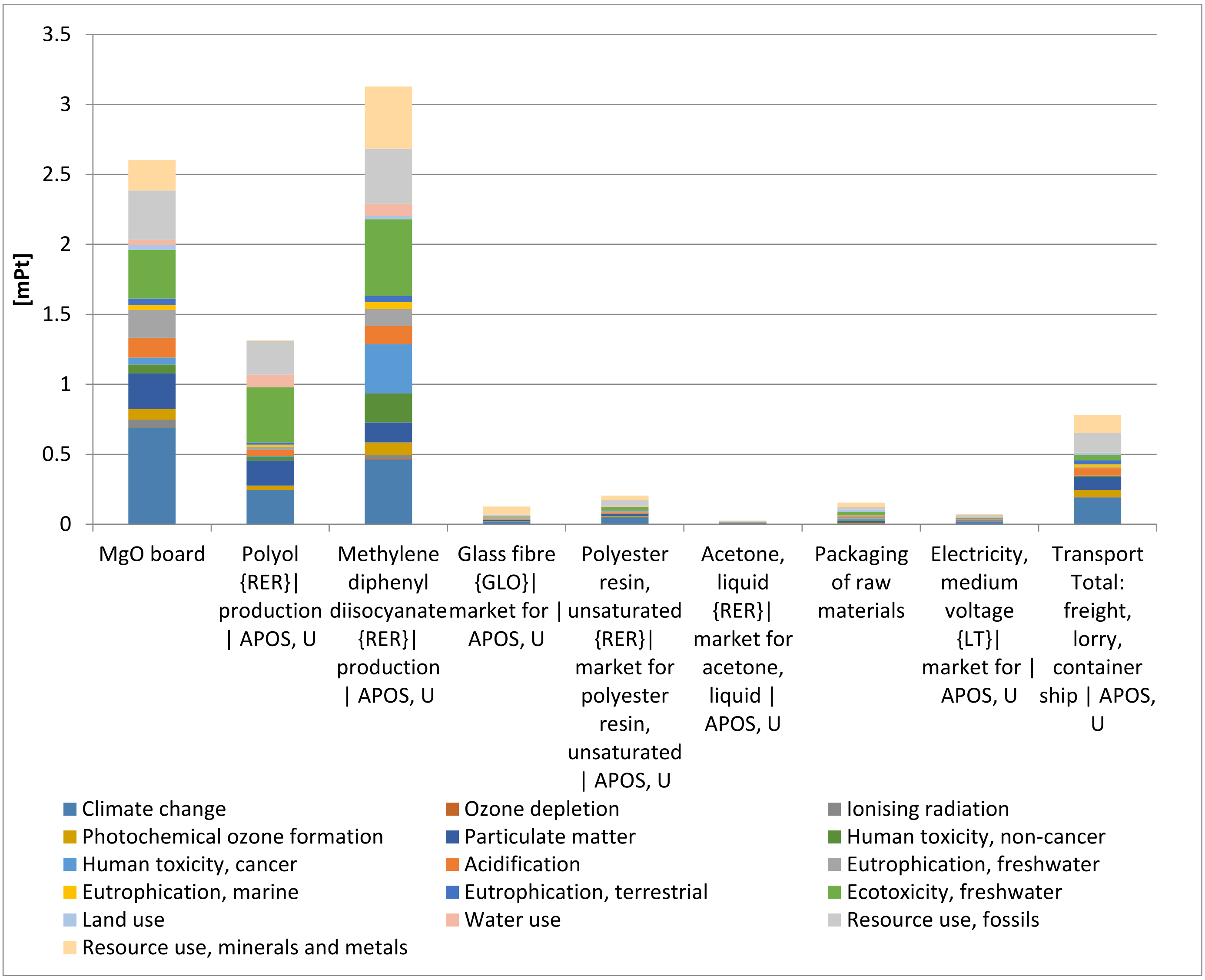


Fig. 23. Normalisation+weighting, single score impact results for unpacked MgO SIP (A1-A3). Method: EN 15804 +A2 Method V1.00 / EF 3.0, 23.5 kg

3.2. Comparative analysis of end-of-life scenarios

The LCA results for the baseline, chemical recycling and re-bonding scenarios of MgO SIP are presented in Figure 24. Comparing the three scenarios, both chemical recycling and re-bonding have lower CO_2 emission to the environment than the baseline scenario. The re-bonding scenario exhibits better results than chemical recycling in more than half of all impact categories, including climate change. For the latter, chemical recycling shows a relative contribution of 73.3% and re-bonding shows a contribution of 66.7%. Detailed data is provided in the table 22, in the appendices section.

Normalised and weighted contributions are presented in the Figure 25 and expressed in mPt. Here, it is depicted that for the climate change category both alternative recycling scenarios have similar impacts and they result in lower environmental burdens compared to the baseline scenario. In mPt, the baseline scenario has a weighted score of 2.4, chemical recycling follows with 1.8 and re-bonding with 1.6. On the other hand, the chemical recycling scenario shows less weighted impacts for the particular matter, human toxicity, and ecotoxicity-freshwater. The latter category is significantly lower for chemical recycling with a weighted value of approximately 0.75 mPt, and around 1.3 mPt for the re-bonding recycling scenario. For the resource use-mineral and metals category, re-bonding shows a lower weighted value than chemical recycling. In the Figure 23 it is presented the single score values for the recycling scenarios, from which we can notice that the chemical recycling scenario contributes almost the same in all impact categories when compared to the re-bonding scenario, and they are both better options than the baseline scenarios.

It is worth mentioning again that chemical recycling process allows a recovery rate of polyol that can substitute up to 25% of conventional polyol use for production of rigid PU/PUR foam, while low-density rigid no-insulation foam can accept more than 50% of recovered polyol [31].

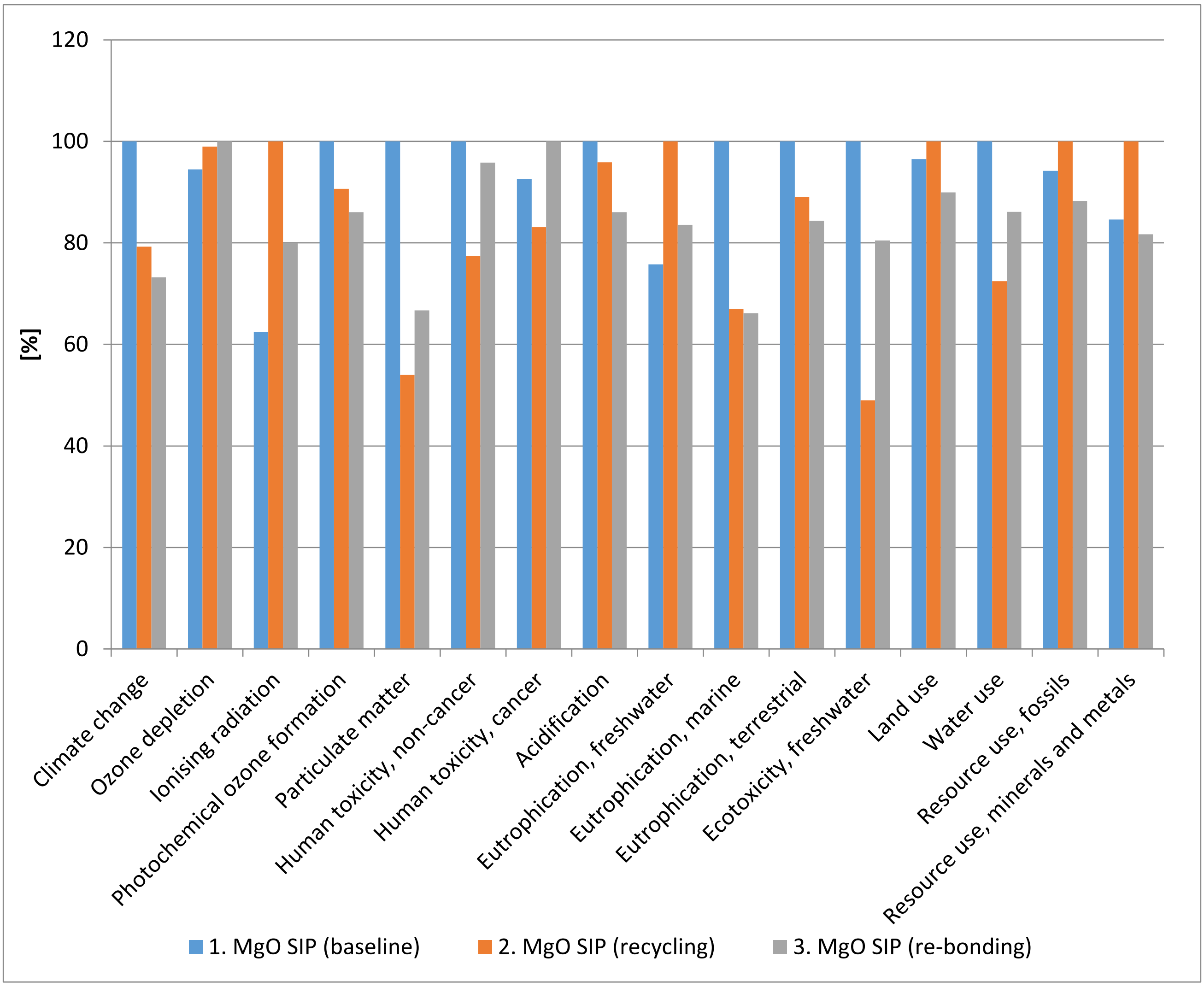


Fig. 24. Characterisation results for recycling scenarios. Method: EN 15804 +A2 Method V1.00 / EF 3.0

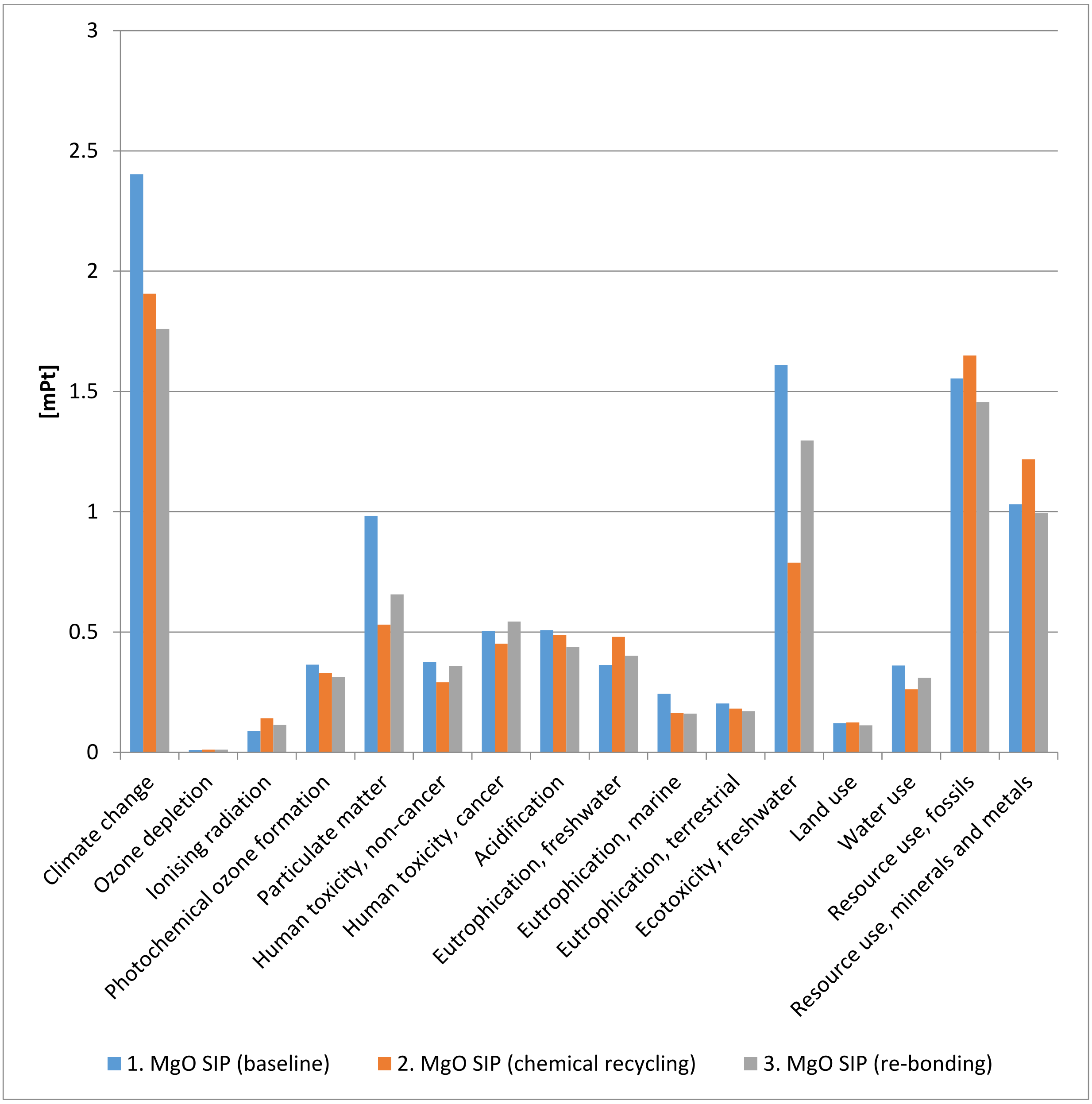


Fig. 25. Normalisation+weighting results for recycling scenarios. Method: EN 15804 +A2 Method V1.00 / EF 3.0

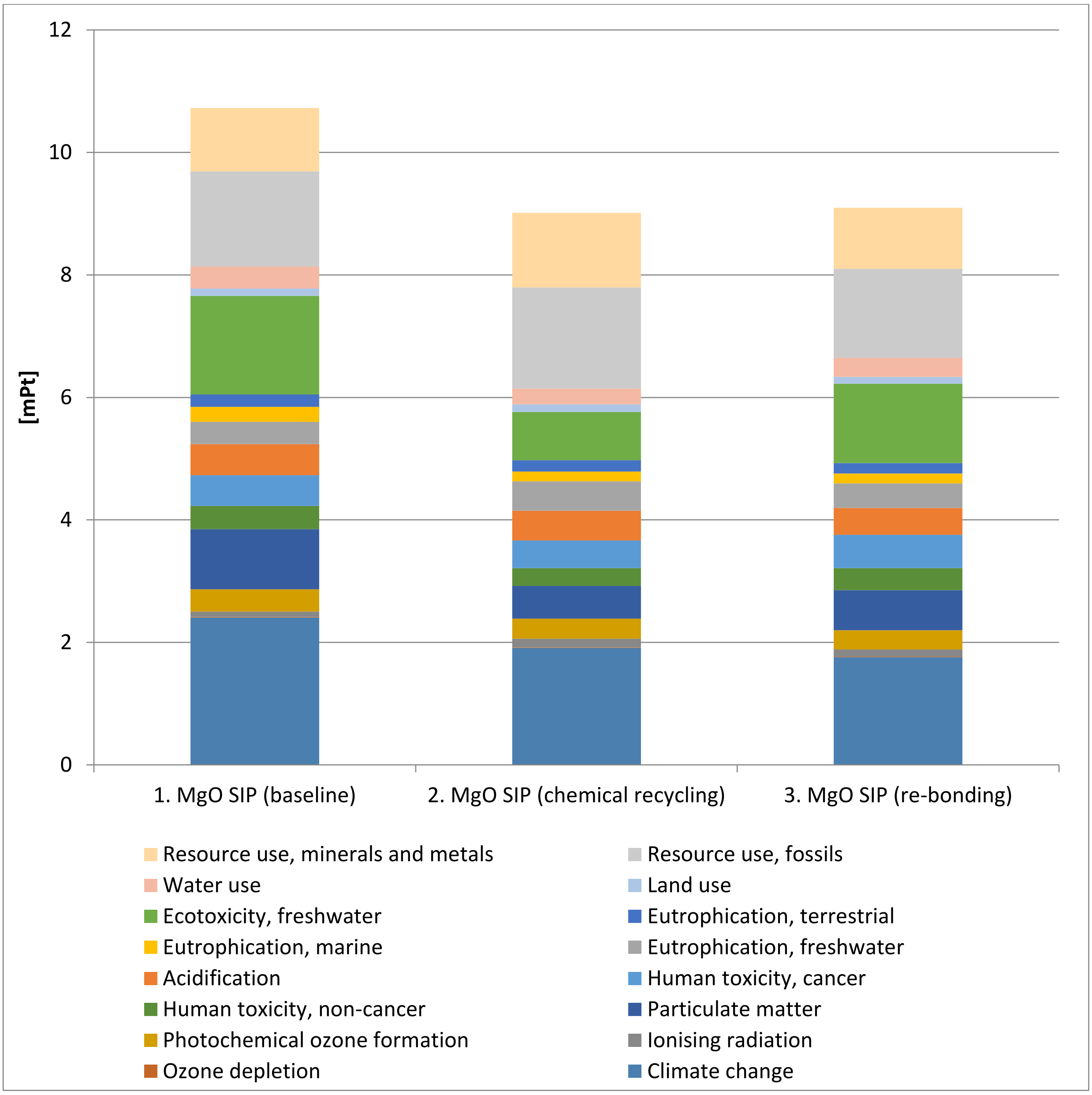


Fig. 26. Normslisation+weighting, single score results for recycling scenarios. Method: EN 15804 +A2 Method V1.00 / EF 3.0

Conclusions

1. The analysed studies on MgO SIP indicate that its use can improve the energy performance of buildings. In addition, its manufacturing process uses lower temperatures than those required to produce other more conventional materials such as Portland cement, which means lower CO_2 emissions and operational costs. However, the carried-out research does not provide clear results of the environmental impacts that MgO SIP can cause during the extraction and transportation of raw materials and at the end of its lifespan, and neither provide information about the benefits of recycling options of MgO.
2. MgO SIP have advantages in terms of fire, mold and plagues resistance against traditional SIP such as OSB and plywood. In terms of thermal insulation, MgO SIP performs better than those fabricated with metal sheets or OSB. The mineral carbonation process that can occur in MgO boards is capable to offset 2.1 kg CO2 emissions for a period of 15 years of the panel use, by functional unit. The production process of MgO boards requires 25-50% less energy use than traditional construction components such as Portland cement.
3. After deconstruction, MgO boards can be separated from the PUR foam core and be utilised as secondary raw material for fertilizer. PUR foam can go be recycled through glycolysis process to recover polyol, which can substitute around 25% of virgin polyol for PUR production, as well as or sealants and adhesives.
4. The cycle stages with higher contributions in almost all impact categories are the product stage (module A1-A3), construction stage (module A5) and end-of-life stage (module C3). The cycle stages with lower contributions in almost all impact categories are transportation (A2 and A4) and deconstruction stage (C1). Product stage accounts for 60-80% of every impact in almost all categories, mainly because of the MgO board and the foam production processes. MgO and foam manufacturing processes contribute to almost 98% of the Climate Change impact category.
5. The analysis of the literature of magnesium oxide structural insulated panels indicates that the environmental benefits of this component, such as thermal insulation and low waste generation, can be outperformed when the environmental burdens of raw materials transportation is not included when conduction analysis such as LCA. The use of MgO manufactured at EU level confirms that when processed locally, the transportation impacts do not exceed the environmental benefits associated with the material
6. The chemical recycling scenario generates approximately 21% of less CO_2 emissions than the baseline recycling scenario, and the re-bonding scenario shows around 25% decrease in CO_2 emissions compared to the baseline recycling scenario. The chemical recycling scenario is recommended to be implemented because the recovered polyol can be use as raw material when mixed with virgin polyol to be used in different chemical processes.

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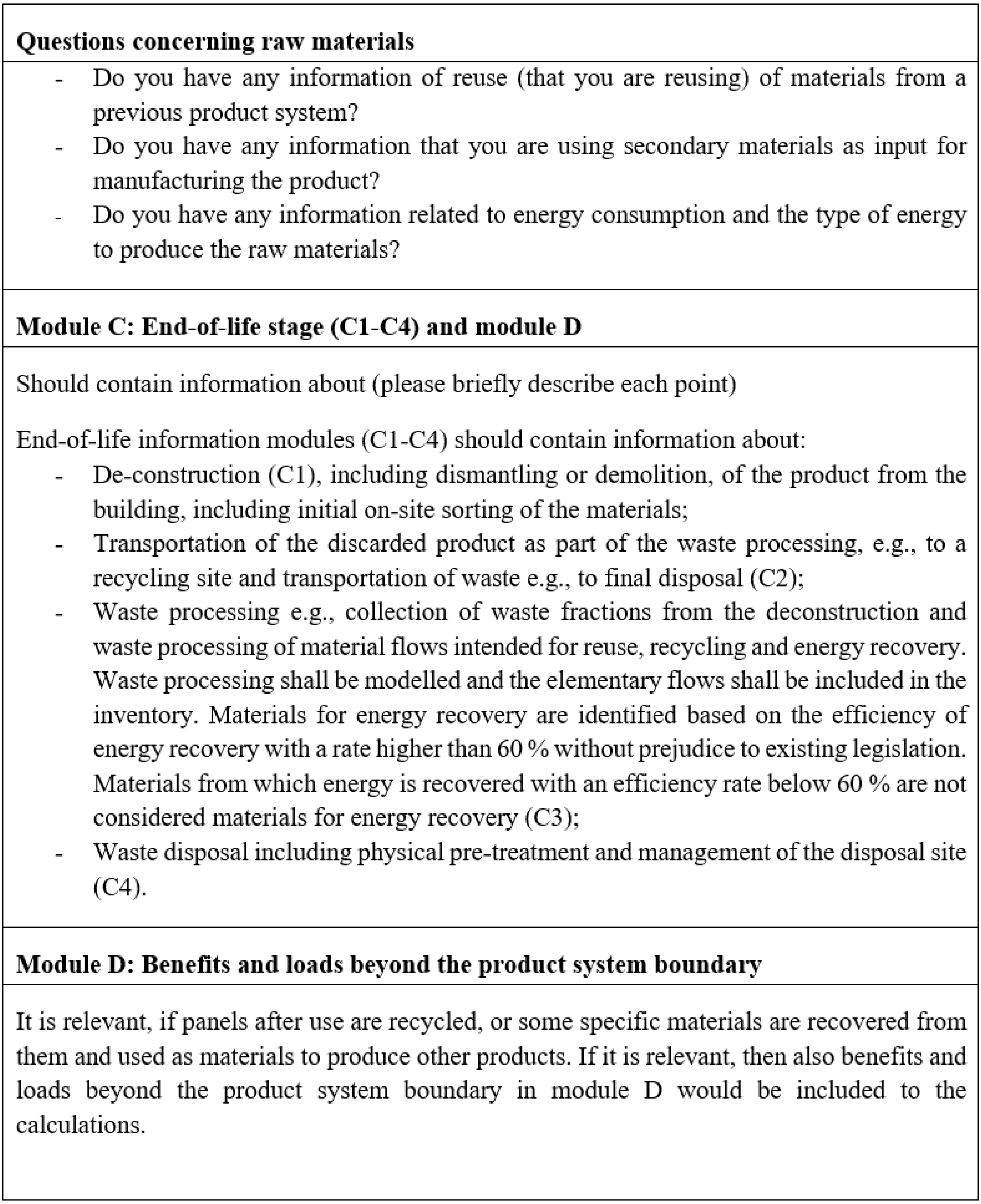
Appendices

Appendix 1. Tables and questionnaires for information gathering sent to the company

The tables here presented were generated to request the selected company the necessary information to conduct the LCA study. All the data gathered from the company was indicated and/or calculated per 1 m2 of insulated panel.



Questions concerning raw materials

- Do you have any information of reuse (that you are reusing) of materials from a previous product system?
- Do you have any information that you are using secondary materials as input for manufacturing the product?
- Do you have any information related to energy consumption and the type of energy to produce the raw materials?

Module C: End-of-life stage (C1-C4) and module D

Should contain information about (please briefly describe each point)

End-of-life information modules (C1-C4) should contain information about:

- De-construction (C1), including dismantling or demolition, of the product from the building, including initial on-site sorting of the materials;
- Transportation of the discarded product as part of the waste processing, e.g., to a recycling site and transportation of waste e.g., to final disposal (C2);
- Waste processing e.g., collection of waste fractions from the deconstruction and waste processing of material flows intended for reuse, recycling and energy recovery. Waste processing shall be modelled and the elementary flows shall be included in the inventory. Materials for energy recovery are identified based on the efficiency of energy recovery with a rate higher than 60 % without prejudice to existing legislation. Materials from which energy is recovered with an efficiency rate below 60 % are not considered materials for energy recovery (C3);
- Waste disposal including physical pre-treatment and management of the disposal site (C4).

Module D: Benefits and loads beyond the product system boundary

It is relevant, if panels after use are recycled, or some specific materials are recovered from them and used as materials to produce other products. If it is relevant, then also benefits and loads beyond the product system boundary in module D would be included to the calculations.

Table 13. A1: Raw material supply and packaging

Material	Specific material type/Component*	Function	Quantity (kg / f.u.)	Health class**	Data source	Packaging material and quantity (kg/f.u.)		Health class**	Data source

Table 14. A2: Transport from suppliers to producer

Material	Vehicle (Truck, Boat, Railway)	Capacity utilisation (incl. Return) %	Type of vehicle	Distance (km)

Table 15. A3: Production of ancillary materials or pre-products

Production of products and co-products	Equipment, power, process duration and energy consumption (kWh/f.u.)	Inputs (Materials, chemicals, water, and their quantities required in the process) kg/f.u.	Outputs (Co-products, waste, spoilage, emissions or wastewater resulting from process) kg, or L, /f.u.	Product	Data source

Table 16. A3: Manufacturing of products and co-products and packing

Production of products and co-products	Equipment, power, process duration and energy consumption (kWh/f.u.)	Inputs (Materials, chemicals, water, and their quantities required in the process) kg/f.u.	Outputs (Co-products, waste, spoilage, emissions or wastewater resulting from process) kg, or L, /f.u.	Product	Data source

Table 17. A4: Transportation from production gate to construction site

Material	Vehicle (Truck, Boat, Railway)	Capacity utilisation (inlc. Return) %	Type of vehicle	Distance (km)

Table 18. A5: Installation into the building

Stages of installation	Equipment, power, process duration and energy consumption kWh/f.u.	Inputs (Materials, water chemicals and their quantities required in the process) kg/f.u.	Outputs (waste, spoilage, emissions or wastewater resulting from process) kg, or L, /f.u.	Data source

Table 19. A5: Production of ancillary materials needed for installation

Material	Specific material type/Component	Function	Quantity (kg / f.u.)	Health class	Data source	Packaging material and quantity (kg/f.u.)		Health class	Data source

Table 20. A5: Transportation of ancillary materials needed for installation

Material	Vehicle (Truck, Boat, Railway)	Capacity utilisation (inlc. Return) %	Type of vehicle	Distance (km)

Appendix 2. Impact results table for MgO SIP, Method EN 15804+A2 V1/EF 3.0 A-D All modules

Table 21.Impact results for MgO SIP, Method: EN 15804 +A2 Method V1.00 / EF 3.0 Modules A-D – All categories

Impact category	**Unit**	**Total**	**(A1-A3)**	**(A4)**	**(A5)**	**C1**	**C2**	**C3**	**C4**	**D total**
Climate change	kg CO2 eq	93.09	66.61	0.88	18.57	0.11	1.4	0.87	11.79	-7.15E+0
Ozone depletion	kg CFC11 eq	8.79E-6	7.85E-6	2.03E-7	8.46E-7	2.28E-8	3.22E-7	7.98E-8	6.92E-8	-6.01E-7
Ionising radiation	kBq U-235 eq	7.81	9.03	0.07	1.12	0.01	0.11	0.46	0.02	-3E+0
Photochemical ozone formation	kg NMVOC eq	0.31	0.25	0.01	0.05	1.47E-3	0.01	1.93E-3	0.01	-1.92E-2
Particulate matter	disease inc.	6.54E-6	5.07E-6	7.39E-8	9.85E-7	1.34E-7	1.27E-7	1.33E-8	3.44E-7	-2.08E-7
Human toxicity, non-cancer	CTUh	4.7E-6	4.23E-6	1.15E-8	4.53E-7	7.48E-10	2.05E-8	8.18E-9	5.7E-8	-8.53E-8
Human toxicity, cancer	CTUh	4E-7	3.56E-7	2.59E-10	4.1E-8	2.65E-11	5.61E-10	2.25E-10	6.03E-9	-4.58E-9
Acidification	mol H+ eq	0.46	0.38	0.01	0.09	1.11E-3	0.01	4.66E-3	0.01	-3.73E-2
Eutrophication, freshwater	kg P eq	0.02	0.02	5.8E-5	3.19E-3	3.64E-6	1.05E-4	8.41E-4	4.92E-5	-5.79E-3
Eutrophication, marine	kg N eq	0.16	0.09	1.74E-3	0.03	4.89E-4	2.87E-3	8.17E-4	0.05	-7E-3
Eutrophication, terrestrial	mol N eq	0.97	0.77	0.02	0.15	0.01	0.03	0.01	0.06	-6.45E-2
Ecotoxicity, freshwater	CTUe	3.59E+3	3.28E+3	10.45	3.38E+2	0.87	17.4	12.09	41.95	-1.12E+2

Impact category	**Unit**	**Total**	**(A1-A3)**	**(A4)**	**(A5)**	**C1**	**C2**	**C3**	**C4**	**D total**
Land use	Pt	1.25E+3	1.21E+3	17.1	1.1E+2	0.31	24.68	14.13	5.01	-1.26E+2
Water use	m3 depriv	48.78	33.85	0.04	16.2	2.08E-3	0.07	0.25	0.63	-2.27E+0
Resource use, fossils	MJ	1.23E+3	1.03E+3	13.32	2.78E+2	1.45	21.39	17.5	5.87	-1.36E+2
Resource use, minerals and metals	kg Sb eq	8.7E-4	8.4E-4	1.31E-5	9.83E-5	1.78E-7	3.29E-5	3.41E-6	6.98E-6	-1.25E-4
Climate change - Fossil	kg CO2 eq	96.02	69.33	0.88	18.72	0.11	1.4	0.84	11.79	-7.04E+0

Appendix 3. Impact results table for MgO SIP, Method EN 15804+A2 V1/EF 3.0 A-D All modules

Table 22. Impact results recycling scenarios for MgO SIP, Method: EN 15804 +A2 Method V1.00 / EF 3.

Impact category	**Unit**	**1. MgO SIP (baseline)**	**2. MgO SIP (chemical recycling)**	**3. MgO SIP (re-bonding)**
Climate change	kg CO2 eq	92.43	73.28	67.66
Ozone depletion	kg CFC11 eq	8.73E-6	9.15E-6	9.24E-6
Ionising radiation	kBq U-235 eq	7.45	11.94	9.55
Photochemical ozone formation	kg NMVOC eq	0.31	0.28	0.27
Particulate matter	disease inc.	6.53E-6	3.53E-6	4.36E-6
Human toxicity, non-cancer	CTUh	4.69E-6	3.63E-6	4.49E-6
Human toxicity, cancer	CTUh	4E-7	3.58E-7	4.31E-7
Acidification	mol H+ eq	0.46	0.44	0.39
Eutrophication, freshwater	kg P eq	0.02	0.03	0.02
Eutrophication, marine	kg N eq	0.16	0.11	0.11
Eutrophication, terrestrial	mol N eq	0.97	0.86	0.82
Ecotoxicity, freshwater	CTUe	3.58E+3	1.75E+3	2.88E+3
Land use	Pt	1.24E+3	1.28E+3	1.16E+3
Water use	m3 depriv.	48.61	35.23	41.86

Impact category	**Unit**	**1. MgO SIP (baseline)**	**2. MgO SIP (chemical recycling)**	**3. MgO SIP (re-bonding)**
Resource use, fossils	MJ	1.21E+3	1.29E+3	1.14E+3
Resource use, minerals and metals	kg Sb eq	8.69E-4	1.03E-3	8.39E-4
Climate change - Fossil	kg CO2 eq	95.39	76.67	70.77
Climate change - Biogenic	kg CO2 eq	-3.02E+0	-3.48E+0	-3.18E+0
Climate change - Land use and LU change	kg CO2 eq	0.06	0.09	0.07
Human toxicity, non-cancer - organics	CTUh	2E-7	1.97E-7	2.3E-7
Human toxicity, non-cancer - inorganics	CTUh	3.09E-6	2.61E-6	3.47E-6
Human toxicity, non-cancer - metals	CTUh	1.41E-6	8.29E-7	8.01E-7
Human toxicity, cancer - organics	CTUh	3.36E-7	3.32E-7	4.02E-7
Human toxicity, cancer - inorganics	CTUh	6.68E-16	7.09E-16	6.48E-16
Human toxicity, cancer - metals	CTUh	6.39E-8	2.63E-8	2.87E-8
Ecotoxicity, freshwater - organics	CTUe	7.48E+2	7.32E+2	8.88E+2
Ecotoxicity, freshwater - inorganics	CTUe	1.4E+3	-3.08E+0	1.01E+3
Ecotoxicity, freshwater - metals	CTUe	1.43E+3	1.02E+3	9.81E+2